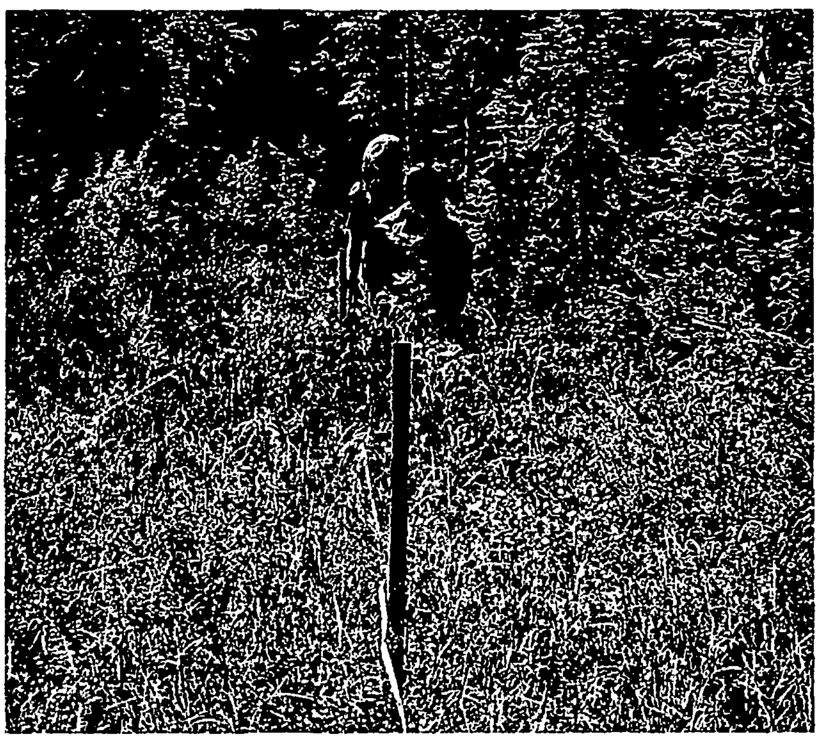
3/05

Bill Adams
6.2.2.3

U.S. Army
Fort Richardson, Alaska

Operable Unit 3
Permafrost Resistivity Investigation
Fort Wainwright, Alaska



March 2005

DEPARTMENT OF THE ARMY
INSTALLATION MANAGEMENT AGENCY
HEADQUARTERS, U.S. ARMY GARRISON, ALASKA
724 POSTAL SERVICE LOOP #6500
FORT RICHARDSON, ALASKA 99505-6500

REPLY TO
ATTENTION OF:

APR 12 2005

Directorate of Public Works

Mr. Bill Adams (ECL-112)
U.S. Environmental Protection Agency
Region 10
1200 Sixth Avenue
Seattle, Washington 98101-9797

Dear Mr. Adams:

Enclosed please find one copy of the "Operable Unit 3, Permafrost Resistivity Investigation," Fort Wainwright Alaska, March 2005, report.

Please contact Ms. Cristal Fosbrook at (907) 384-3044, email cristal.fosbrook@us.army.mil, or Ms. Therese Deardorff at (907) 384-2716, email therese.deardorff@us.army.mil if you have any questions on this report.

Sincerely,

Allan D. Lucht

Allan D. Lucht
Director, Directorate of Public Works

Enclosure

OPERABLE UNIT 3 PERMAFROST RESISTIVITY INVESTIGATION
FORT WAINWRIGHT, ALASKA

LETTER REPORT
March 2005

Prepared for
U.S. ARMY GARRISON ALASKA
DIRECTORATE OF PUBLIC WORKS

Prepared by
U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
AND
OPALIA ENVIRONMENTAL

PREFACE

This report was prepared for the U.S. Army Alaska Directorate of Public Works (DPW) by Beth Astley, Research Physical Scientist, Cold Regions Research and Engineering Laboratory (CRREL); and Colby Snyder, Opalia Environmental, LLC. Beth Astley was the principle investigator for the resistivity investigation and can be reached at 907-384-0513 or Beth.N.Astley@erdc.usace.army.mil. Colby Snyder developed the permafrost model and can be reached at csnyder@opaliaenv.com.

The authors thank Alan Delaney, Ann Staples, Art Gelvin, and Stephanie Saari of CRREL, and Kristen Sturtevant, Patrick Case, and Arlow Linton of the State University of New York at Buffalo for their help with data collection and surveying for this study. This study was funded by the U.S. Army Environmental Center (AEC) under MIPR #4F48R00023. The USAGAK DPW environmental project managers were Therese Deardorff and Cristal Fosbrook.

For this report's purposes, the site is defined as the Birch Hill Tank Farm and the Truck Fill Stand and includes all areas bordering the tank farm at the base of Birch Hill, for a total of 160 acres of Fort Wainwright (referred to herein as the "site." When "Birch Hill" is stated, it refers to the landmass, not the Birch Hill Tank Farm). Five operable units (OUs) have been defined on the 915,000-acre Fort Wainwright. The Birch Hill Tank Farm and the Truck Fill Stand are located within OU3; therefore, this is the only OU addressed in this report.

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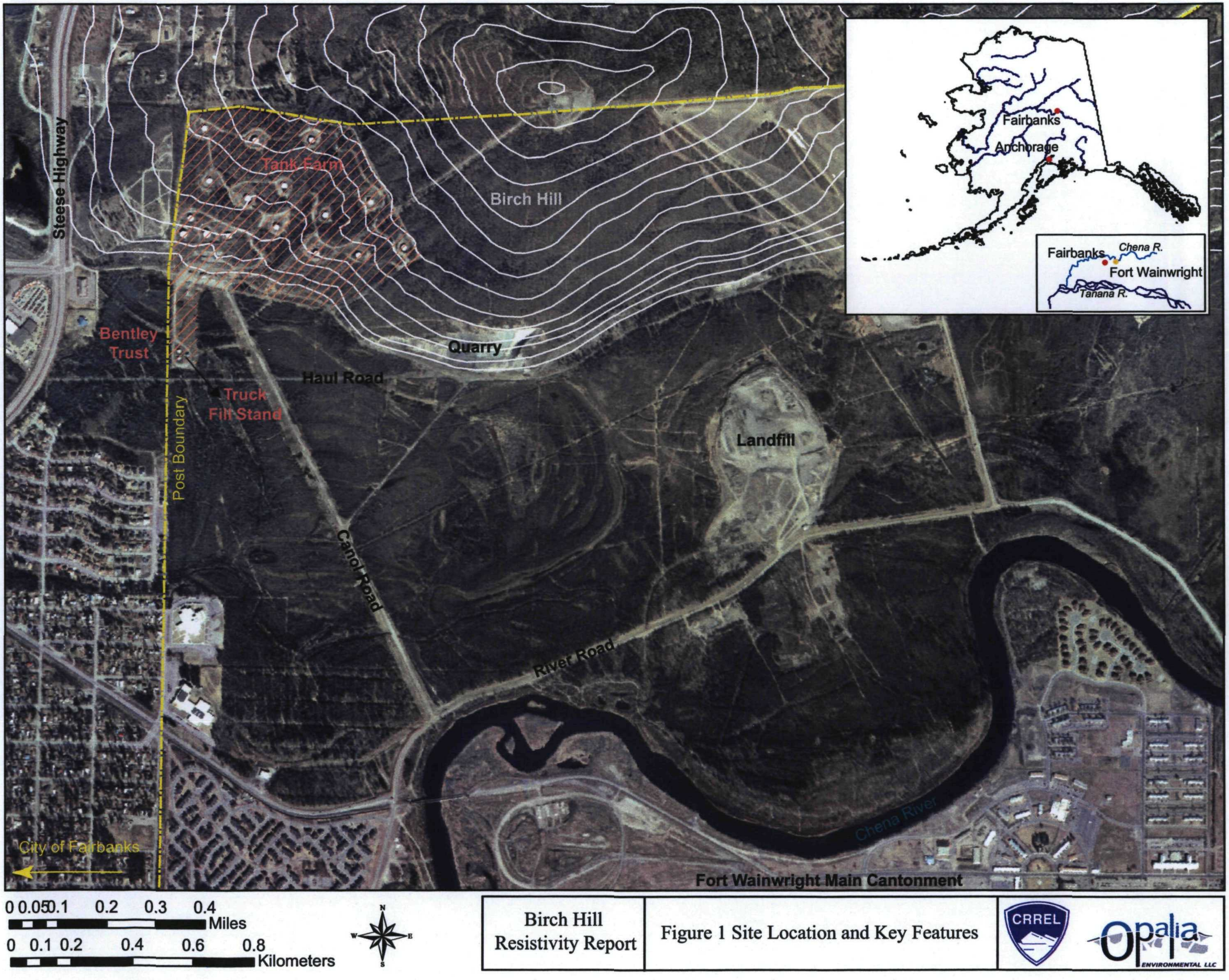
EXECUTIVE SUMMARY

The Birch Hill Tank Farm, part of Operable Unit 3 (OU3) on Fort Wainwright, Alaska, was used as an Army fuel storage facility from 1943 to 1993 (Fig. 1). Contaminants from the use of petroleum products including benzene, 1,2-dichloroethane (DCA), and 1,2-dibromoethane (EDB) persist above maximum contaminant levels (MCLs) in groundwater at the Birch Hill Tank Farm. A federal facilities agreement (FFA) meeting held in January 2004 identified areas where additional information was needed to improve the accuracy of a groundwater model being developed by CH2MHill. These data gaps included the depth to the bottom of massive permafrost bodies identified at the base of Birch Hill, the existence of permafrost lenses in the Truck Fill Stand, the locations of bedrock faults, and the presence of permafrost within the fault zones. This study used resistivity to attempt to resolve these data gaps within the alluvial portion (area at the base of Birch Hill where alluvium overlies the bedrock) of OU3 and Bentley Trust (private land adjacent to Fort Wainwright). This report discusses the results of the 2004 resistivity investigation and our current knowledge of permafrost distribution at the Birch Hill Tank Farm.

This investigation used direct current (DC) resistivity to measure the apparent resistivity of the subsurface along six profiles. The most significant findings were as follows:

1. A massive permafrost body found on Bentley Trust in the area between Lazelle Road and the "thaw" channel is frozen to a maximum of approximately 52 m (170 ft) depth and covers an area of up to 8 acres. A massive permafrost body located at the base of Birch Hill between the Truck Fill Stand Fence and Canol Pipeline extends to a depth of 40 m (131 ft).
2. Relatively small bodies of sporadic permafrost were confirmed south of the above-mentioned massive permafrost bodies at the base of Birch Hill. The shallow sporadic bodies intersect the groundwater table, but do not extend to bedrock. Beneath the shallow permafrost, the saturated aquifer is free of permafrost to approximately the bedrock interface. Resistivity data suggest that deep permafrost layers may exist near the bedrock interface. This complex layering of frozen and thawed ground has not been confirmed with ground truth but could affect groundwater flow.
3. Permafrost bodies were identified within the Truck Fill Stand and at the base of Birch Hill, confirming that permafrost persists in some cleared/heavily disturbed areas. Some of these areas have been cleared for as long as 58 years.
4. The permafrost in the vicinity of Canol Road and Pipeline is much more complex then previously thought, with a highly irregular distribution of permafrost, specifically at depth.
5. The bedrock of the Gully Fault trace is mostly thawed near the base of Birch Hill, but contains sporadic permafrost along its trace to the southwest.
6. The bedrock of the Cemetery Fault trace is frozen near the base of Birch Hill.



Birch Hill Resistivity Report	Figure 1 Site Location and Key Features

INTRODUCTION

Operable Unit 3 (OU3), on Fort Wainwright, contains soil and groundwater contamination associated with fuel storage activities conducted from 1943 to 1993 at the Birch Hill Tank Farm. The groundwater has been monitored since the early 1990's; contaminant concentrations on Birch Hill currently remain above MCLs.

A tracer study conducted in 2003 concluded that the groundwater flow pathways from the bedrock aquifer underlying the lower Tank Farm source area to the alluvial aquifer at the base of Birch Hill are complex, not fully understood, and likely involve bedrock structures (CH2MHill 2003). As a result of the tracer testing, it was decided to utilize an alternate groundwater modeling approach which required the development of a refined conceptual geologic model for the site. CRREL was tasked with developing this model using available borehole and geophysical data including ground-penetrating radar, resistivity, shallow seismics, and borehole logging (gamma, SP, and resistivity). The final geologic model includes the configuration of the alluvial and bedrock aquifers, a plausible bedrock structure network, regional faults, and permafrost within the study area. CH2MHill was tasked with developing a groundwater model that utilized this geologic model; first, however, critical data gaps needed to be filled. These included, specifically, the depth to the bottom of massive permafrost bodies identified at the base of Birch Hill, the existence of permafrost lenses in the Truck Fill Stand, the locations of bedrock faults, and the presence of permafrost within the fault zones. It was determined that these data gaps could be investigated using resistivity techniques. This study focused on the alluvial portion (area at the base of Birch Hill where alluvium overlies the bedrock) of OU3 and Bentley Trust (privately owned land adjacent to Fort Wainwright).

A three-dimensional permafrost model (part of the Birch Hill Geologic Model) for the OU3 area was generated with Dynamic Graphics EarthVision software. The inputs include borehole, geophysical, and vegetation data. The borehole data set includes over 1,000 borings and monitoring wells installed between Birch Hill and the Chena River, with the densest set of boreholes found at the site. The vegetative analysis and subsequent model input was generated from evaluation of aerial photography and field surveys of the site and surrounding areas. The geophysical inputs are resistivity and GPR data. The model was updated after completion of the 2004 resistivity survey. For a detailed discussion of the permafrost model see Appendix A.

Permafrost

Permafrost is perennially frozen ground that occurs wherever mean annual temperatures remain at or below freezing for two or more years. It is present in the Fairbanks area because of the region's sub-arctic climate, which has a mean annual temperature of 2.9°C. The uppermost layer of ground, or the "active layer," undergoes seasonal freezing and thawing, whereas much of the material below the active layer remains frozen throughout the year. In Fairbanks, the depth of the active layer is usually 1 to 2 m, but can be as small as a few centimeters where massive permafrost is present in vegetated areas.

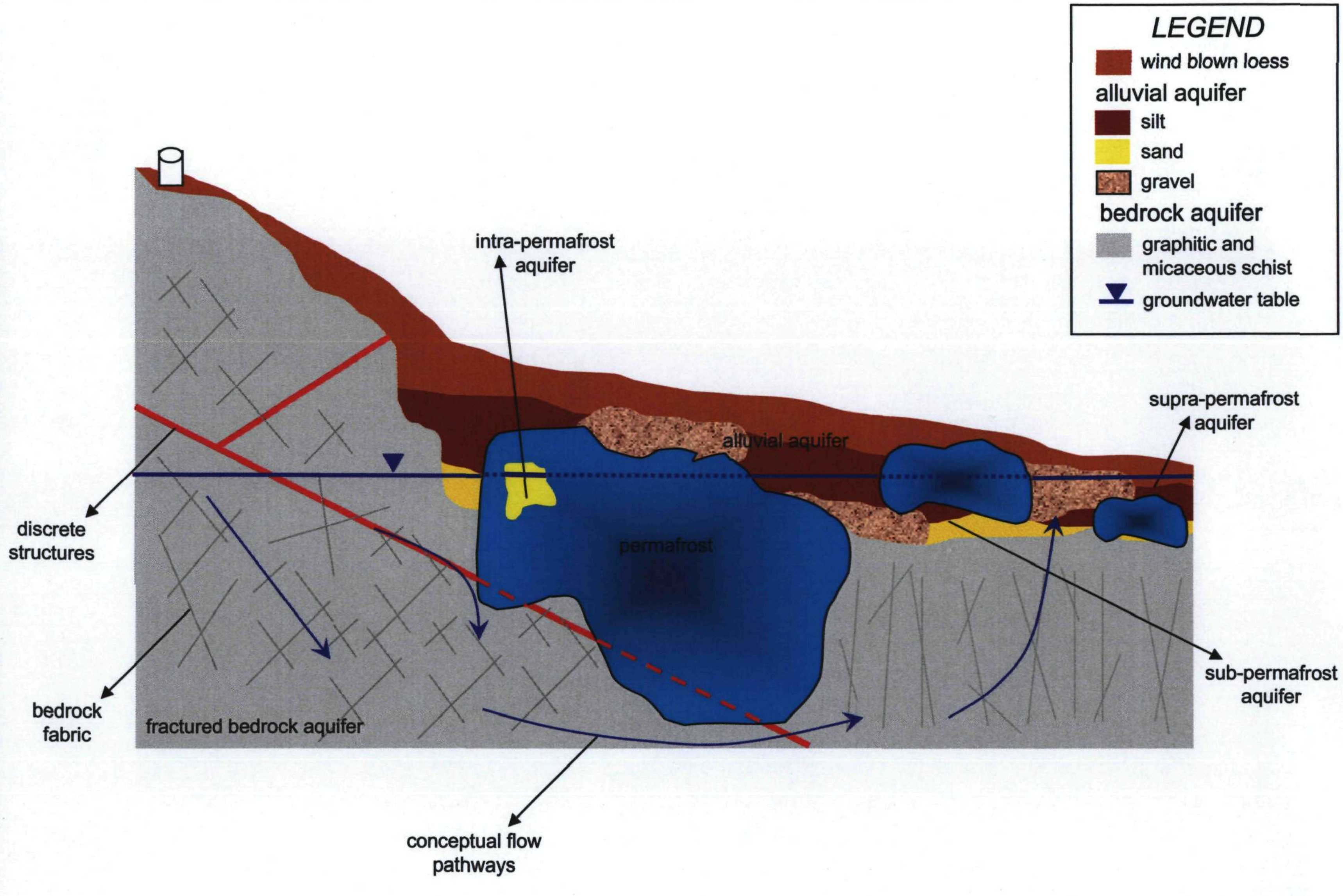
The spatial complexity of the permafrost here reflects past geologic events, including relocation of the meandering river channels, degradation associated with saturated groundwater flow, climatic events, and surface disturbances, such as from human activity. Thick organic layers insulate permafrost and prevent or slow its degradation. Anthropogenic disturbances, such as excavation and construction, as well as conductive heat flux from groundwater flow, generally degrade permafrost. Permafrost also tends to be absent under deep water bodies. The incidence angle of solar radiation causes permafrost to be absent on south-facing slopes, such as the Tank Farm on Birch Hill.

The rate of permafrost degradation is controlled by many factors mentioned above as well as soil type. Frozen gravels typically contain 1–4% of their volume as ice, while silts contain about 40–60%. Because of the greater ice content in silts, they require a larger amount of thermal energy to degrade, and it can take considerably longer for them to thaw compared to gravel. At OU3, permafrost would be expected to degrade faster in gravel layers, while more ice-rich layers remain frozen. The presence of boreholes within the Truck Fill stand that encountered several layers of alternating permafrost and thaw support this idea.

Frozen gravels are generally thaw-stable. This means that as the pore ice melts, the soil matrix does not compact or settle substantially. In contrast, frozen silts are not thaw-stable. As frozen silts melt and the soil collapses, depressions on the ground surface are formed. Where these depressions are present, the term "thermokarst" is used to describe the topography of the land surface. New wetland creation is occurring rapidly in central Alaska as a result of thawing of frozen silts. As much as 50% of Tanana Flats Training Area is undergoing permafrost degradation and thermokarst development (Jorgenson et al. 1999).

Groundwater aquifers

At OU3, previous borehole and GPR data show that three separate groundwater aquifers exist at this site because of the presence of permafrost. A supra-permafrost aquifer may develop above the permafrost, a confined or semi-confined sub-permafrost aquifer may be found below the permafrost, and an intra-permafrost aquifer occurs where free water is found within permafrost (Fig. 2). These permafrost aquifers occur primarily in the alluvial aquifer except between the base of Birch Hill and the Haul Road where permafrost is present to varying degrees in the bedrock. The depth to groundwater within the alluvial aquifer ranges from 3 to 5 m (9.8 to 16.4 ft) within the study area.



Birch Hill Resistivity Report	Figure 2 Conceptual Groundwater Flow Pathways	CRREL Opalia Environmental LLC

Resistivity

The resistivity (or conversely conductivity) of a material depends on how easily an electrical current can flow through it. Resistivity is measured in ohm-meters (Ω m), defined as the electrical resistance measured on a one-meter cubic sample. Materials with low resistivity allow current to flow more easily than those with high resistivity. In general, sediments of small grain size, such as clay and silt, have low resistivity values and sediments of large grain size, such as gravel, have higher resistivity values. The presence of water can lower the resistivity values significantly. Resistivity of soils and rocks are determined by porosity, moisture content, cation/anion concentration of moisture, temperature, whether the pore water is frozen or thawed, and the mineralogy of soil or rock (Tables 1, 2).

Table 1. Resistivities of some common rocks, soils, and waters (modified from Loke 1999, Telford et al. 1990, and Sellmann et al. 1976). Rocks and soils highlighted in gray are present at OU3.

Material	*Resistivity ohm-m*
Igneous and Metamorphic Rocks	
Granite	$5{,}000–10^6$
Basalt	$1{,}000–10^6$
Slate	$600–4 \times 10^7$
Marble	$100–2.5 \times 10^8$
Quartzite	$100–2 \times 10^8$
Schist (calcareous and mica)	$20–10^4$
Schist (graphitic)	10–100
Sedimentary Rocks	
Sandstone	8–4,000
Shale	20–2,000
Limestone	50–400
Soils and Waters	
Clay	1–100
Fairbanks Silt	40–100
Alluvium	10–800
Groundwater (fresh)	10–100
Sea water	0.2

Table 2. DC resistivity values for various materials measured at OU3 (modified from Peapples et al. 2000).

Material	*Resistivity (ohm-m)*
Silt (moist)	50–340
Silt (dry)	1,500
Silt (frozen)	**1,000–8,000**
Alluvium	25–1,000
Alluvium (frozen)	**1,000–18,000**
Quartz-Muscovite Schist (weathered)	80–1,800
Quartz-Muscovite Schist (competent)	2,000–5,000
Graphitic Schist (competent)	2,000–3,000

Frozen sediment and bedrock offer greater resistance than in an unfrozen state, making permafrost relatively easy to identify using measurements of ground resistivity or magnetic induction. At temperatures less than 0°C, the ground temperature has a large influence on resistivity (Fig. 3). This has significance at OU3 because degrading (or warm) permafrost would be expected to have a lower resistivity than cold, stable permafrost.

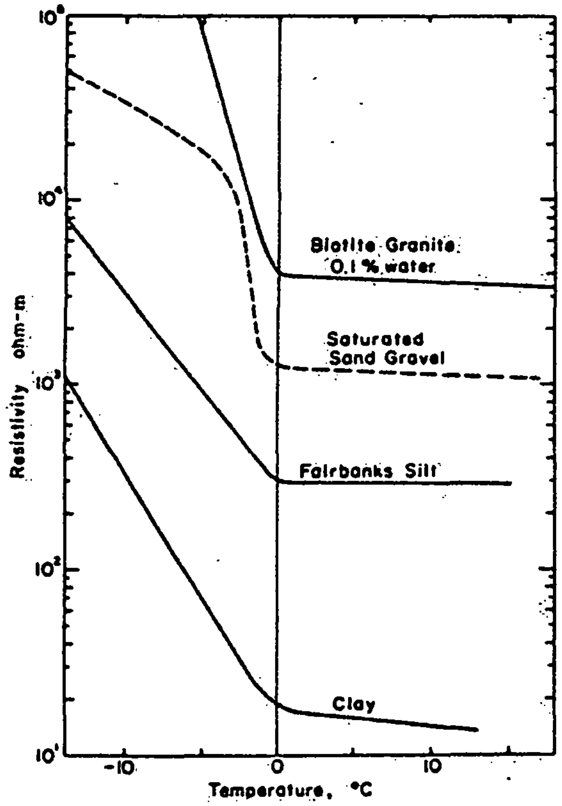


Figure 3. Resistivities of several soils and one rock type as a function of temperature (Hoekstra and McNeill, 1973).

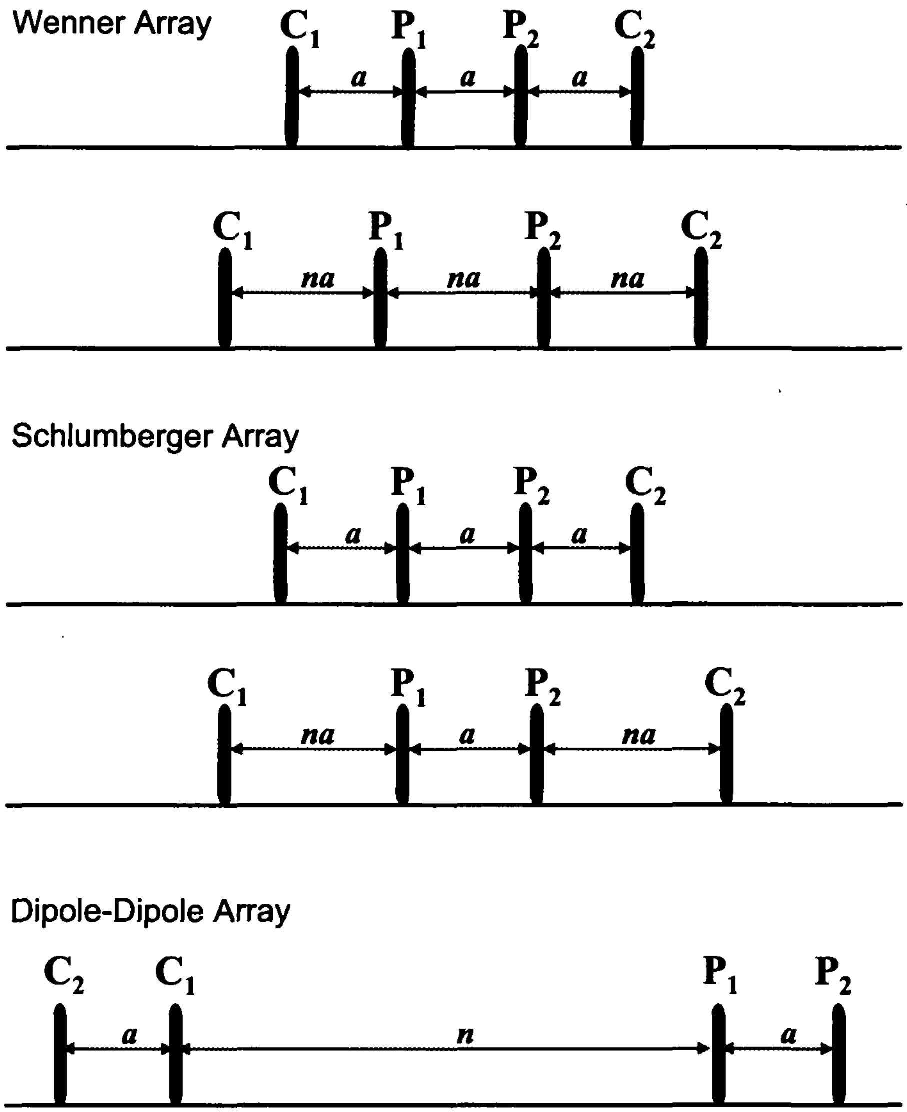
During electrical resistivity data collection, an electrical current from a battery is driven into one pair of electrodes (charged electrodes), and the induced voltage between two potential electrodes is then measured. An apparent resistivity is calculated from the ratio of voltage to current using the following formula:

$$R_a = k\,(V/I)$$

where

R_a = apparent resistivity
k = the geometric factor determined by the arrangement of the electrodes
V = measured voltage
I = current.

Data can be collected using several different electrode configurations, called arrays. Three common array types are shown in Figure 4.



C denotes the charged electrodes

P denotes the potential electrodes

a is the distance between electrodes

n is the depth level set by the user

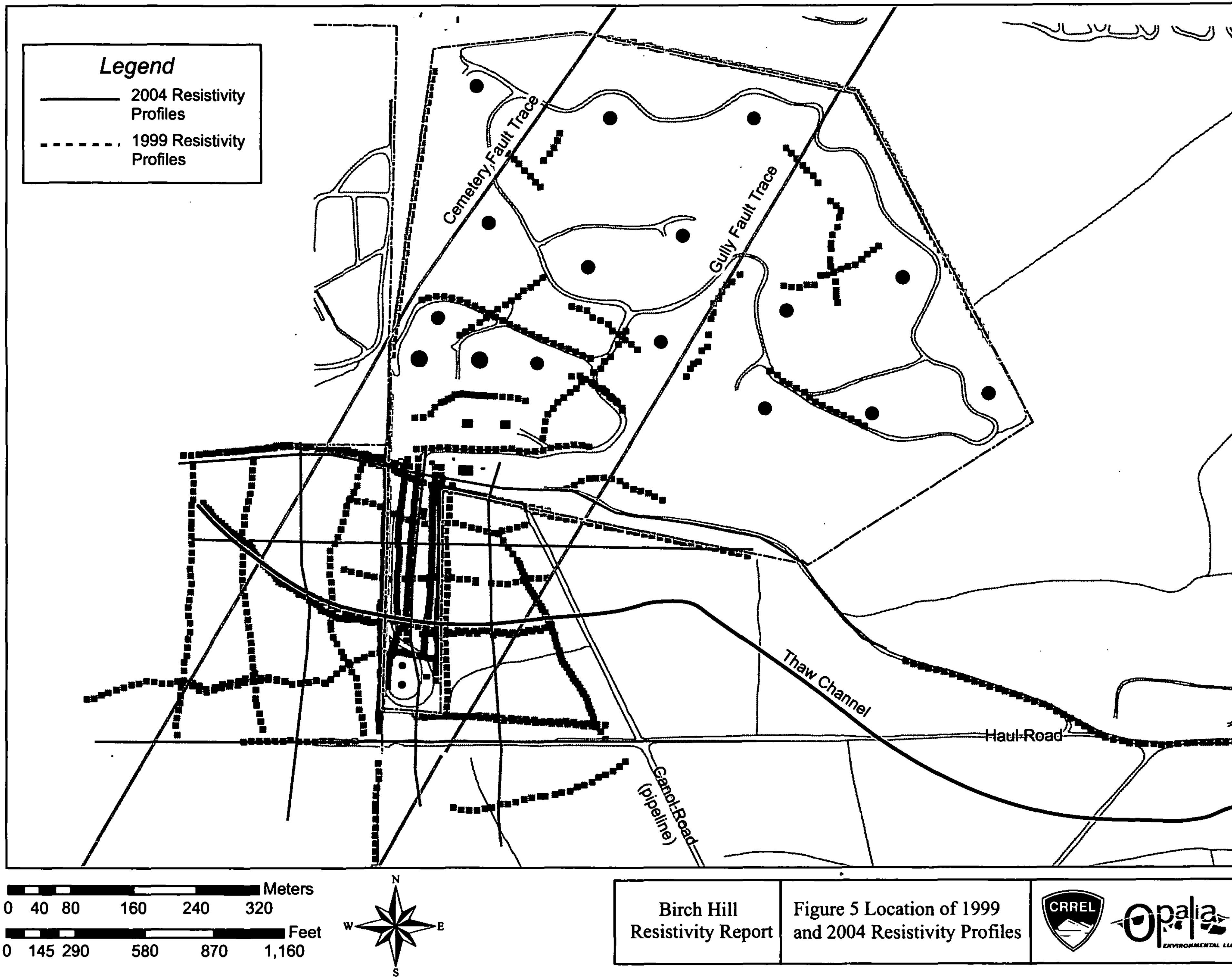
Figure 4. Schematics of the three resistivity array types used during this investigation.

PREVIOUS WORK

1999 Resistivity survey

An extensive resistivity survey was done at OU3 in 1999 consisting of 20 soundings and 63 profiles located on both Birch Hill and in the alluvial sediments in the floodplain of the Chena River (Fig. 5) (Astley et al. 1999). This survey indicated generally low resistivities on Birch Hill but with trends showing higher bedrock resistivity west of the Gully Fault and north of Tank 316. In the alluvium, the 1999 data showed sharp contrasts between low and very high resistivity where permafrost was present. Subsequently in 2001, boreholes drilled on Bentley Trust confirmed the extent of permafrost defined by the 1999 resistivity survey.

The results of the 1999 survey were used to update the permafrost model. The most important change was in the Thaw Channel on Bentley Trust. This area was previously thought to be completely thawed all the way to the Steese Chapel, but the resistivity data showed the Thaw Channel is frozen from near the surface to far below the water table about 100 m west of CRREL-12 (AP-6571). However, this interpretation was never confirmed with a borehole. The 1999 data also suggested sporadic permafrost at the base of Birch Hill and in the Truck Fill Stand, but because of the discontinuous nature of the permafrost in those areas, the data were difficult to interpret using the 1999 data collection technique. Since 1999, advances in resistivity meters and computer capabilities have allowed for data to be collected in a more efficient and comprehensive manner.



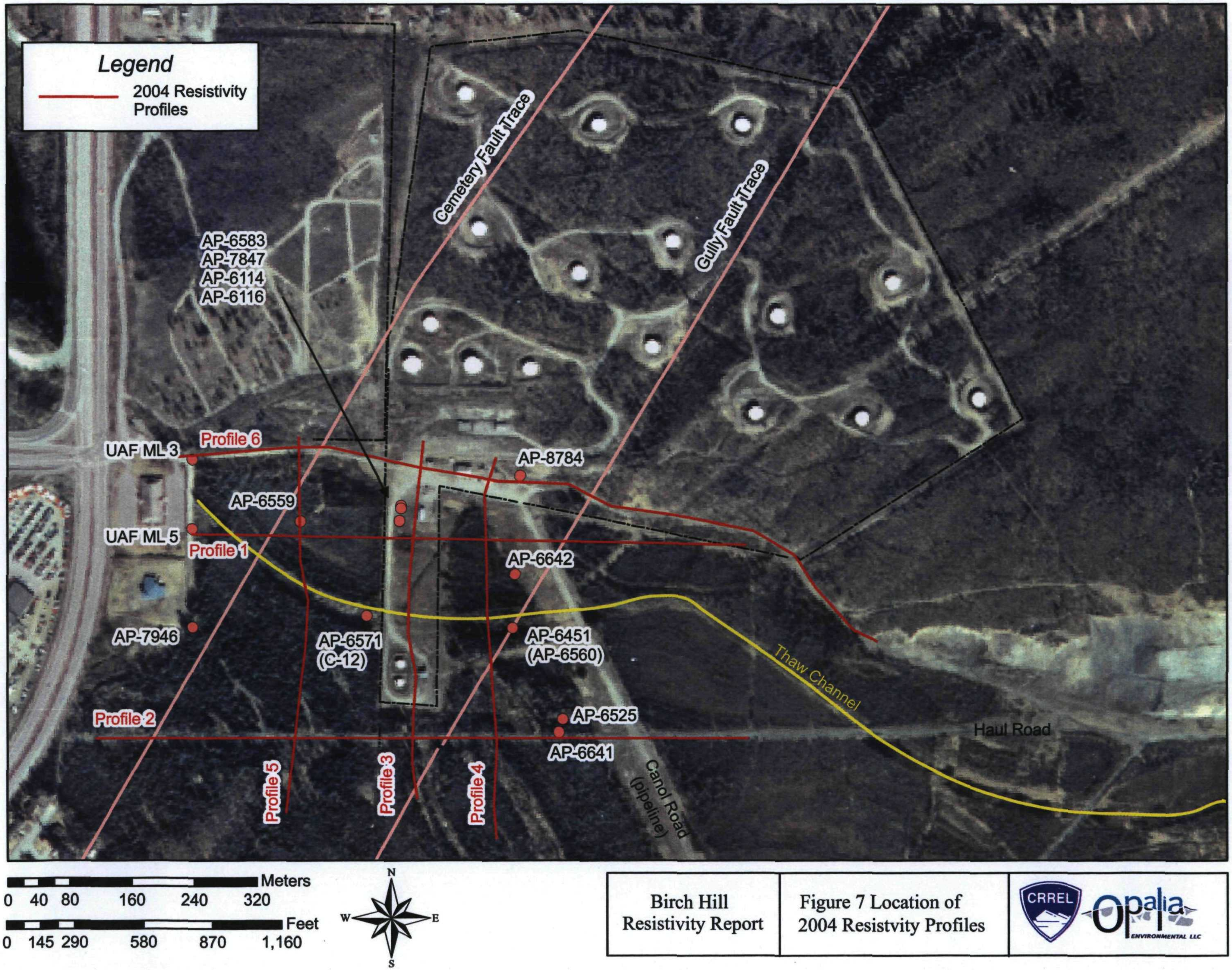
Birch Hill Resistivity Report	Figure 5 Location of 1999 and 2004 Resistivity Profiles

METHODS

Resistivity

This study used an Iris Instruments Syscal Pro-ten, 10-channel switch resistivity meter and a 96-electrode cable with 5-m electrode spacing (Fig. 6). At each electrode location, salt water (NaCl) was applied to ensure good voltage coupling between the electrode and the ground for more accurate readings. A total of six profiles was collected (Fig. 7). Profiles 3, 4, and 5 were 475 m while Profiles 1, 2, and 6 were 715, 830, and 850 m, respectively. For profiles longer than 475 m (the maximum array length with 5-m electrode spacing), the first 24 electrodes were moved to the end of the line to lengthen the profile in what is called a "roll-along." Multiple roll-alongs were performed on Profiles 1, 2, and 6. Data collection parameters are provided in Appendix B, Table 1.

Figure 6. Resistivity meter control board (top photograph), meter, marine battery and laptop computer (middle photograph), and cable and electrode setup (bottom) used for data collection.



Birch Hill Resistivity Report	Figure 7 Location of 2004 Resistvity Profiles

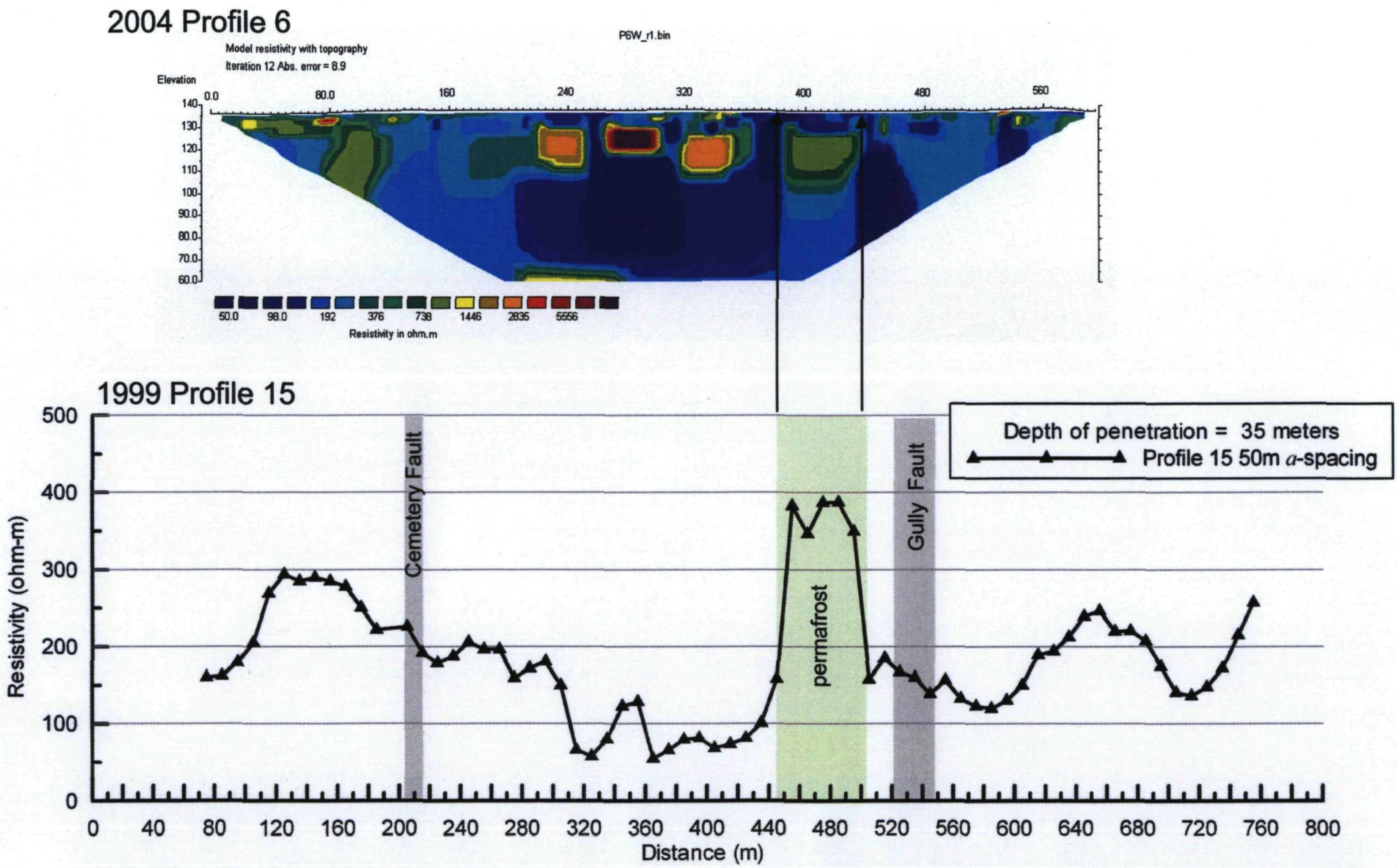
The Wenner, Schlumberger, and dipole–dipole arrays were used to collect resistivity data (Fig. 4). The Wenner array has a stronger signal, resulting in a survey that has deeper penetration than the dipole–dipole array and may be more successful in an area containing background noise than other surveys. The Wenner array is the most sensitive to horizontal features. The dipole–dipole array has a weaker signal, especially as the "n" spacing increases, creating a more shallow survey, and is the most sensitive to vertical features. The Schlumberger array has an intermediate signal strength, resulting in greater depth penetration than the dipole–dipole, and is generally sensitive to both vertical and horizontal features. At OU3, we hypothesized that the Wenner array would be the best array type for mapping the top of bedrock and the bottom of massive permafrost, and the dipole–dipole array would detect vertical changes in resistivity, such as fault zones. We collected Shlumberger array data on some of the lines in order to compare it to the dipole–dipole and Wenner array data and assess the value of this array type at OU3.

The resistivity data were processed using the RES2DINV version 3.53 software. The raw data were imported in a program called Prosys, which allows the user to edit the data points and add topographic information as well as export the data in a form used by RES2DINV. The data were imported into RES2DINV and data points that were obvious outliers were removed from the data set. The profiles were then run through the inversion process using the "robust inversion" settings until the change in error between iterations was less than 1%.

The methods described above allowed CRREL to conduct a more focused and refined resistivity survey with improved ability to discern local-scale permafrost features as well as allowing greater depth penetration. Figure 8 shows a comparison of the 1999-versus-2004 results from a single profile.

Data collection

Profiles were collected along six profiles at the site and on the adjacent Bentley Trust property (Fig. 7). The profile locations were selected to provide information on depth to the bottom of permafrost, to map the Cemetery and Gully Faults south of Birch Hill, and to better define discontinuous permafrost in the Truck Fill Stand area.



The 2004 data was more useful to interpret discreet permafrost bodies than the 1999 data set. The area highlighted in yellow on Profile 15 with high resistivity is in the vicinity of the original pump-house that is documented to have been built on permafrost. The location of this high resistivity anomaly correlates well with an anomaly on Profile 6.

Birch Hill Resistivity Report	Figure 8 Comparison of 1999 Resistivity Profile 15 to 2004 Profile 6	CRREL Opalia ENVIRONMENTAL LLC

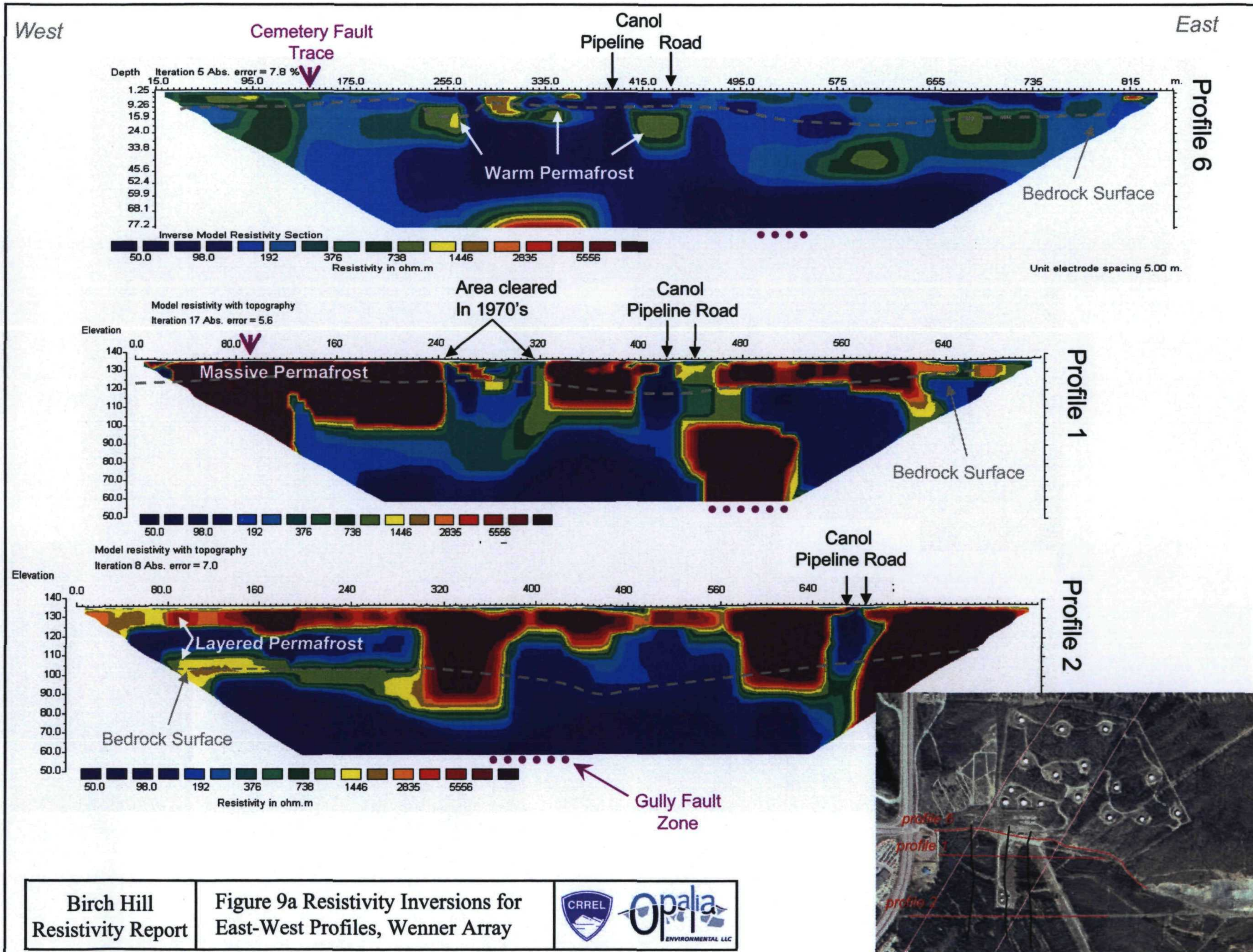
A map of the profile locations was submitted to the Army and Bentley Trust Landowners prior to the start of this study. A right-of-entry permit was obtained to access the Bentley Trust portion of the study area. GPS waypoints were created from the preliminary map, and were used to locate the lines in the wooded areas. Locations of the profiles were flagged and brush was cleared from the lines to allow a person to freely walk along each profile. The profiles were marked every 50 m with a wooden stake. The position of each stake was determined with a Trimble ProXR GPS, and the elevation was surveyed with a total station. Also, marking paint was sprayed on the ground to indicate the location of the electrodes, spaced every 5 m. Locations of anthropogenic features that could potentially affect the resistivity results, such as power lines, fences, buried pipes, and monitoring wells, were noted.

RESULTS

Resistivity anomalies from the inverted datasets with values over 2,000 ohm-meters were interpreted as frozen soil. Values less than 2,000 ohm-meters were evaluated on a case-by-case basis because of the change in resistance as permafrost nears 0°C. Evidence such as permafrost in nearby borehole logs was weighed heavily when deciding how to interpret high resistivity anomalies. The active layer in the Fairbanks area is generally between 1 and 2 m in thickness from the ground surface, but can be greater during winters with little snowfall and very cold temperatures. Because the survey was completed in June, some of the seasonally frozen ground, or "active layer," may not have completely thawed. If the survey was completed in September, some of the very shallow (0-2 m or 0 to 6.6 ft) high resistivity anomalies detected in the June 2004 dataset related to seasonal frost would presumably be absent. For data interpretation, if the high resistivity anomaly extended greater than 2 m below the subsurface, it was interpreted to be permafrost. If it did not extend greater than 2 m below the surface, it was assumed to be seasonal frost within the active layer and was not included in the permafrost model. The Fort Wainwright 3-D permafrost model was then updated using permafrost boundary information from the inverted data.

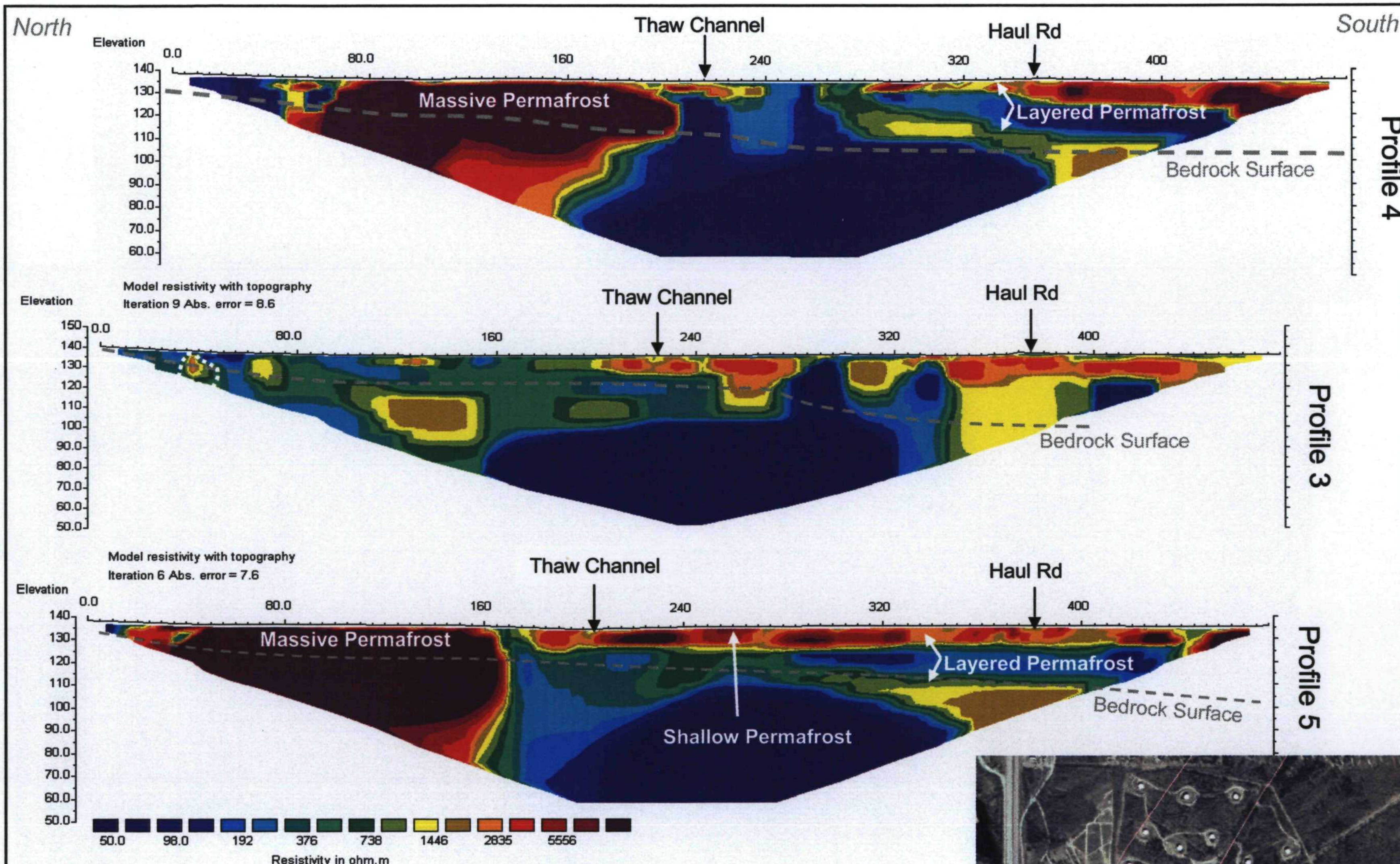
The wenner and dipole-dipole array inversions were found to be very effective when used together to determine permafrost boundaries. The dipole-dipole inversions were the most accurate for detecting shallow permafrost, while the wenner inversions were most useful for deep permafrost. The Slumberger inversions did not prove to be as useful for permafrost interpretations.

Figure 9 contains the inverted resistivity results for the Wenner array. All the inversions can be found in Appendix B. Figure 10 shows the permafrost model along the 2004 resistivity profiles.



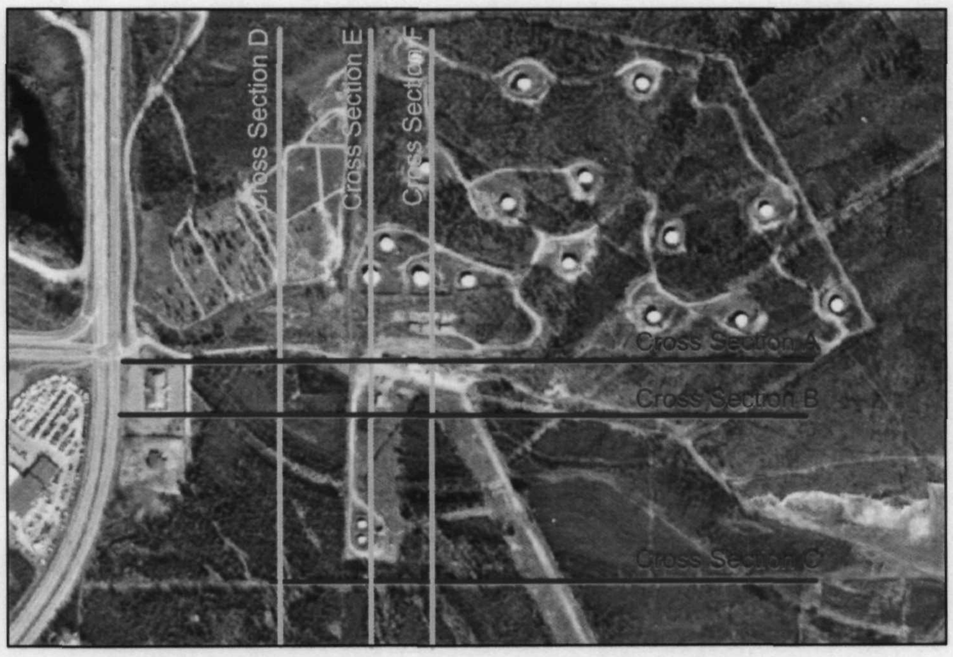
Birch Hill Resistivity Report

Figure 9a Resistivity Inversions for East-West Profiles, Wenner Array



Birch Hill Resistivity Report

Figure 9b Resistivity Inversions for North-South Profiles, Wenner Array



LEGEND

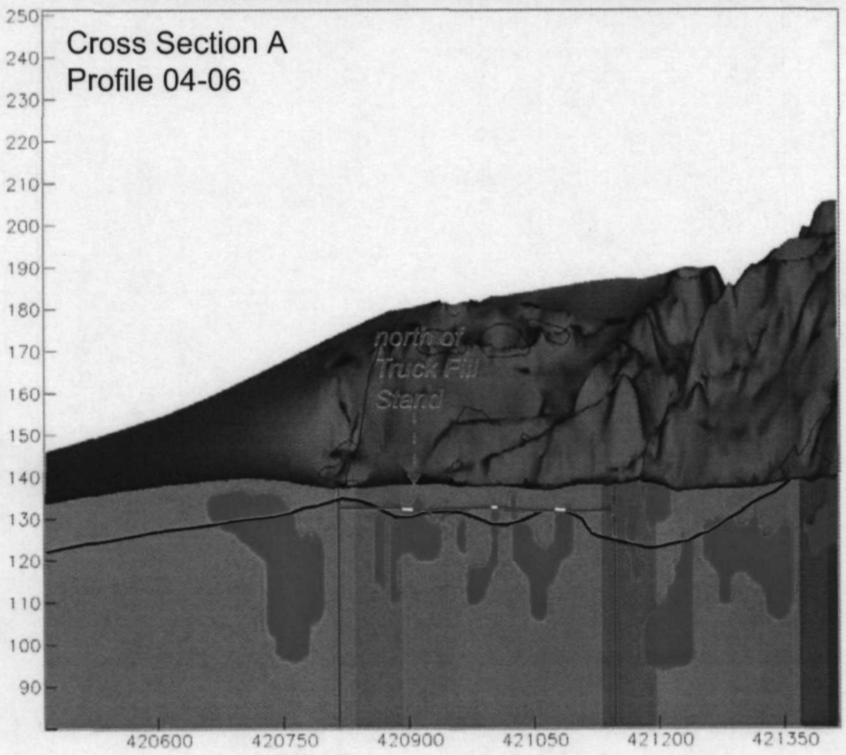
- permafrost
- thaw
- alluvial-bedrock interface
- regional faults
- projection of regional fault traces through the alluvial aquifer
- groundwater table
- potentiometric surface

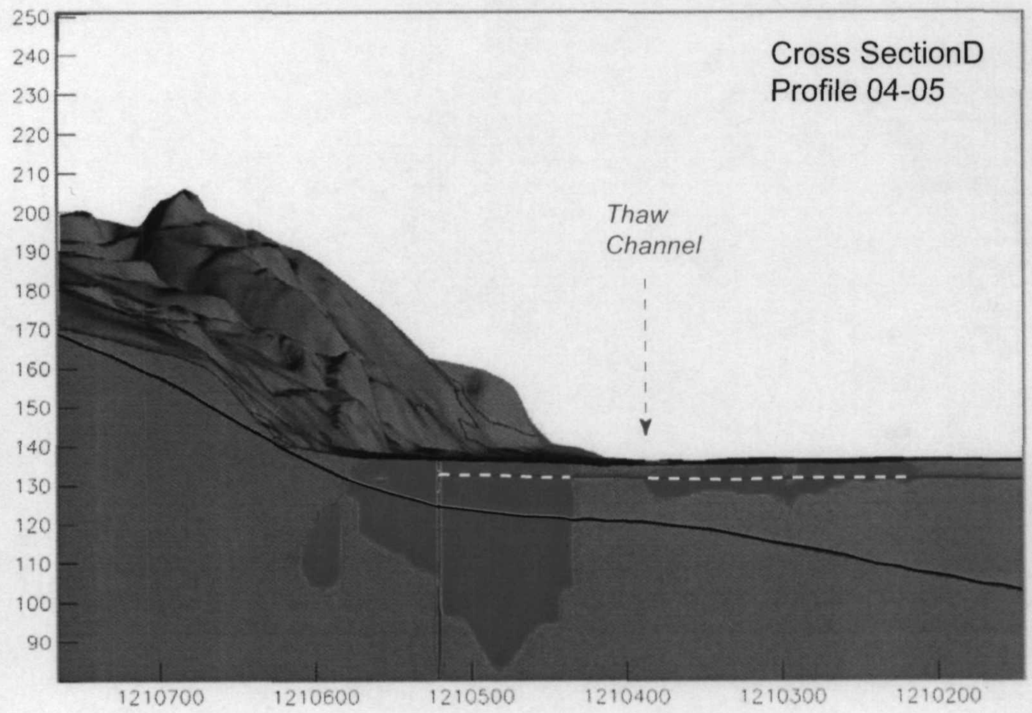
Notes:

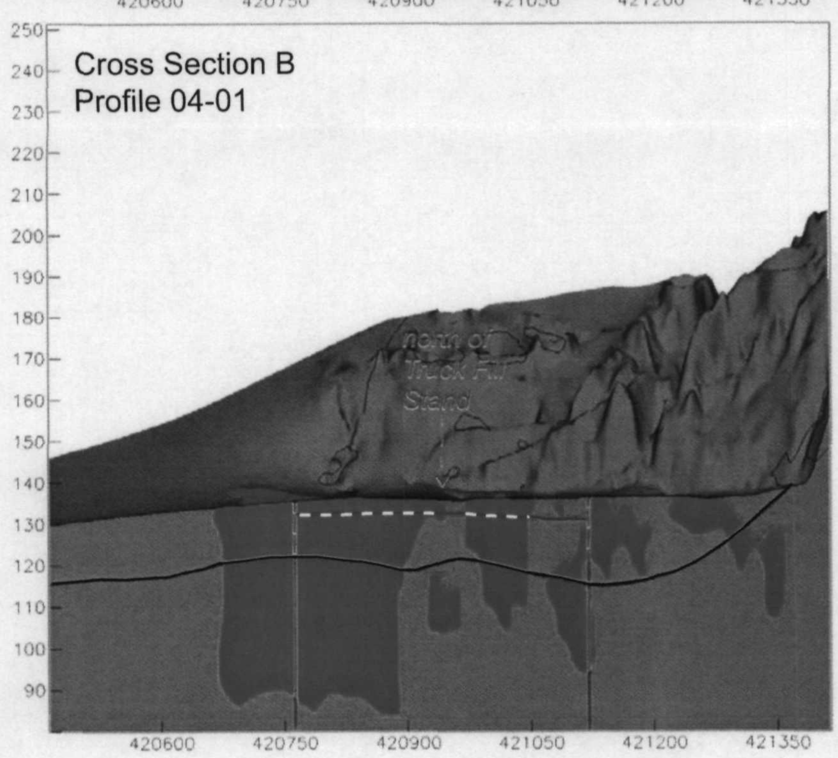
a. Vertical Exaggeration on Cross Sections A, B and C is 5

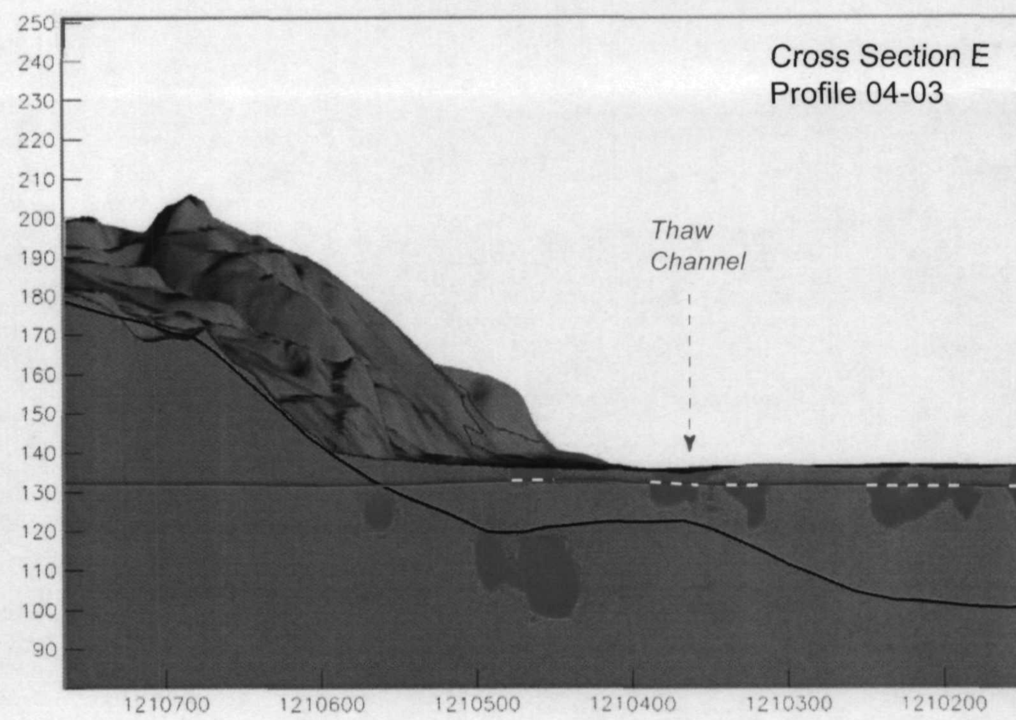
b. Vertical Exaggeration on Cross Sections D, E and F is 2.5

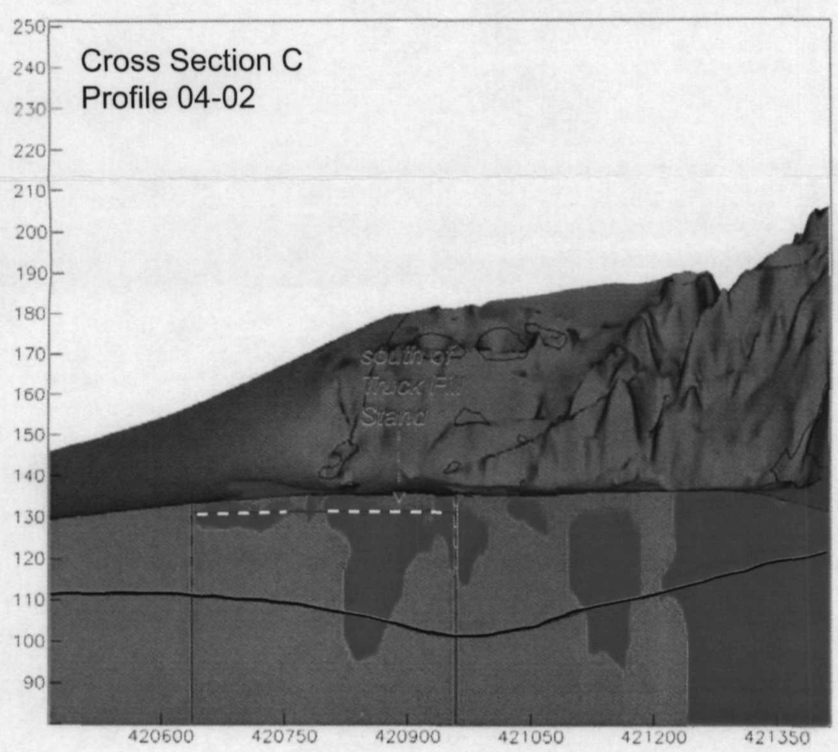
c. Areas where groundwater table does not extend are areas where it is not defined due to lack of groundwater elevation data

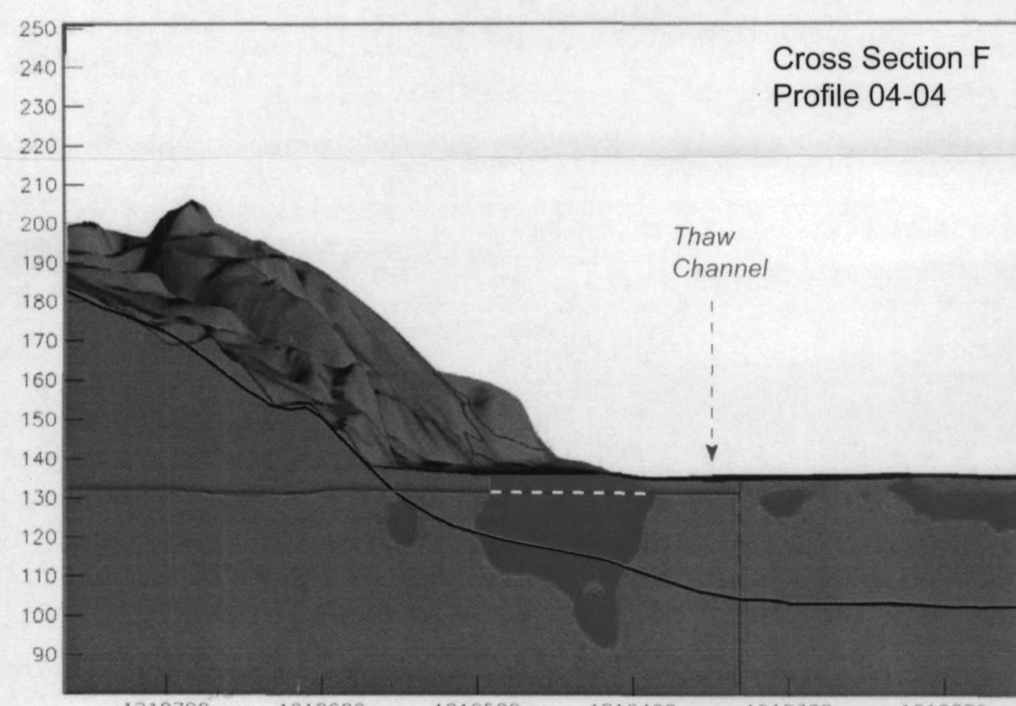












Birch Hill Resistivity Report	Figure 10 2004 Resistivity Profiles Permafrost Model Cross Sections	CRREL	Opalia ENVIRONMENTAL LLC

Profile 1

Profile 1 started on Bentley Trust near the Steese Chapel and monitoring well UAFML5 and ended 715 m to the east on Fort Wainwright near the fence at the base of Birch Hill (Fig. 9a). Profile 1 shows extensive permafrost on Bentley Trust from approximately 25 m to 245 m along the profile length, ending at approximately the Truck Fill Stand fence. This zone represents one large body of permafrost. The top of permafrost is generally less than 1 m (3.3 ft) from the surface and the depth to the base of permafrost on Profile 1 averages about 45 m (148 ft).

At the Truck Fill Stand Fence, the permafrost thins and becomes sporadic, occupying depths between 3 and 8 m across the Truck Fill Stand. Permafrost was found during drilling in nearby boreholes (AP-6114, AP-6116, AP-6583, and AP-7847) at a depth of approximately 6 m (18 ft).

Another large permafrost body is found starting at the east edge of the Truck Fill Stand (at 330 m along the profile) and extends westward about halfway to the Canol Pipeline. The permafrost in this area is just below the surface. A thawed zone exists from about 405 m to 435 m along the profile and it appears to be thawed to bedrock. At 435 m on profile 1, deep permafrost is encountered starting at approximately 20 m (60 ft) below the ground surface. The dipole–dipole data show high resistivity below this area at about 28-m depth. The area halfway from the Truck Fill Stand fence to the Pipeline is likely characterized by warm (approaching 0°C), locally sporadic permafrost. A nearby borehole, AP-6642, shows fairly extensive permafrost but the permafrost lenses are separated by discrete areas of thaw. The permafrost in this borehole is also classified as varying from well to poorly bonded, indicating variations of soil thermal conditions and ice content. This makes the permafrost signal in the area more difficult to interpret versus where the permafrost is massive.

Several permafrost bodies are present from 435 m to the end of the line, ranging from 1- to 40-m depths. Some extend to bedrock and others end above the bedrock interface.

Profile 1 crossed the Cemetery Fault and the Gully Fault just south of the base of Birch Hill. The resistivity data indicate that the bedrock at the Cemetery Fault trace is within the massive permafrost body on the west side of Profile 1; the Gully fault trace appears partially frozen within the bedrock where it intersects Profile 1 (Fig. 9a).

Profile 2

Profile 2 was collected from east to west along the Haul Road, parallel to Lazelle Road, starting at GPR line 94-53 and ending at 830 m, near the Steese Highway. From 0 to 130 m, thick permafrost was encountered to depths greater than 50 m. At Canol Road, a thaw bulb exists under Canol Road and Pipeline. To the west of the pipeline, permafrost is present again from 180 to 265 m to depths of as great as 40 m. From 265 m to the end of the line, several discontinuous permafrost bodies separated by thaw were detected (Fig. 9a).

Profile 2 also crossed the Cemetery and Gully Fault traces; however, only the Gully Fault Zone is modeled because of the geometry of the resistivity measurements. The Cemetery Fault would be located at about 790 m along Profile 2, where the resistivity data did not penetrate into bedrock. In order to collect data along Profile 2 for the Cemetery Fault, the line would need to extend across the Steese Highway. The area on Profile 2 that is hypothesized to be the Gully Fault Zone has low resistivity and appears completely thawed within the bedrock. However, permafrost exists within the alluvium above the Gully Fault Zone.

Profile 3

Profile 3 was collected from north to south starting at the base of Birch Hill, extending through the center of the Truck Fill Stand, and across the Haul Road, ending at 475 m. There were several, previously unidentified, discontinuous permafrost lenses found on this profile (Fig. 9b). It was also recently discovered that the eastern portion of the Truck Fill Stand (the area east of the access road) was not completely cleared until the early 1970s. After this time, the area was relatively undisturbed, thereby supporting our finding that significant permafrost persists here at shallow to intermediate depths.

A high resistivity anomaly was detected at approximately 100–135 m at significant depths of approximately 16–35 m (60–115 ft) below the ground surface. This anomaly could be a remnant permafrost body within bedrock. It is located near AP-6583, which had permafrost extending from 6- to 10-m depths (18 to 30 ft). However, the borehole ended in permafrost.

High resistivity at depths ranging from 1 to 10 m between 205 and 285 m along the profile could represent shallow, discontinuous permafrost. If these areas are frozen, they may affect groundwater flow within the central Truck Fill Stand in the area just north of the Thaw Channel, because they tend to be present just below the groundwater table (approximately 3 m below the ground surface).

Several permafrost bodies represented by high resistivity anomalies are present from just south of the Truck Fill Stand fence (at approximately 335 m) to 440 m. These anomalies extend to about 13 m below the ground surface.

Profile 4

Profile 4 was collected from north to south from the break in slope at the base of Birch Hill to south of the Haul Road. A large permafrost body was detected from approximately 80 to 190 m, extending to depths of 40 m. Thin permafrost was detected near the surface from the Haul Road to the end of the line at 475 m (Fig. 9b). A deeper layer of permafrost is suggested starting at approximately 280 m extending to 400 m. The signal begins within the alluvium and extends in to the bedrock, effectively separating the alluvial aquifer from the bedrock aquifer in this area. Profile 5 shows a similar resistive layer near the bedrock interface. If this is truly representative of the permafrost distribution (there is no direct ground truth available to confirm this signal), then communication between the bedrock and alluvial aquifer via upward vertical gradients is most likely to occur from approximately 180 to 280 m along Profile 4, focused within the vicinity of the Thaw Channel.

Area boreholes also indicate the presence of warm, discontinuous permafrost. AP-6642, AP-6525, and AP-6641 are found in the vicinity of Profile 4 and show alternating poorly and well-bonded permafrost. The nature of the permafrost in these wells is supportive of the observed alternating frozen and thawed signal seen along Profile 4.

A 5-m-thick layer containing high resistivity was detected where Profile 4 crosses the Thaw Channel. The dipole–dipole data suggest a decrease in resistivity within this layer right in the center of the Thaw Channel, but does not indicate that thaw is present. This high resistivity anomaly is puzzling because the borehole AP-6451 (later installed as well AP-6560) and a series of nested piezometer points did not show signs of frozen ground near the surface. It is suspected that this high resistivity either represents seasonal frost that was not thawed in June or that the 5-m electrode spacing and the resolution of the resistivity model is not great enough to detect thawed zones of less than 5-m width between closely spaced permafrost bodies. However, because this high resistivity zone exists largely above the location of the water table, it will have no effect on groundwater flow through the Thaw Channel. Just below this highly resistive layer, a resistivity low exists where the alluvium is thawed, supporting the assumption that the Thaw Channel is the first point of potential communication between the bedrock and alluvial aquifers.

Profile 5

Profile 5 was collected north to south from the break in slope at the base of Birch Hill at Lazelle Road to south of the Haul Road on Bentley Trust. A large permafrost body (also detected on Profile 1) was found from approximately 20 to 160 m along the profile. The depth to thaw under permafrost is at least 45 m. This profile confirms that the bedrock in this area is frozen, including the projection of the Cemetery Fault trace. South of this large permafrost body, discontinuous permafrost was detected, ranging from just below the surface to approximately 7-m depth. These discontinuous permafrost bodies are not frozen into the bedrock (Fig. 9b).

Low resistivity anomalies were found within the alluvium and bedrock from 160 to 190 m. These low anomalies may indicate areas of higher hydraulic conductivity. It is interesting that on both Profiles 4 and 5, some of the lowest resistivity values occur just south of massive, deep permafrost, in the vicinity of the Thaw Channel. The low resistivity at these locations suggests higher groundwater flow rates.

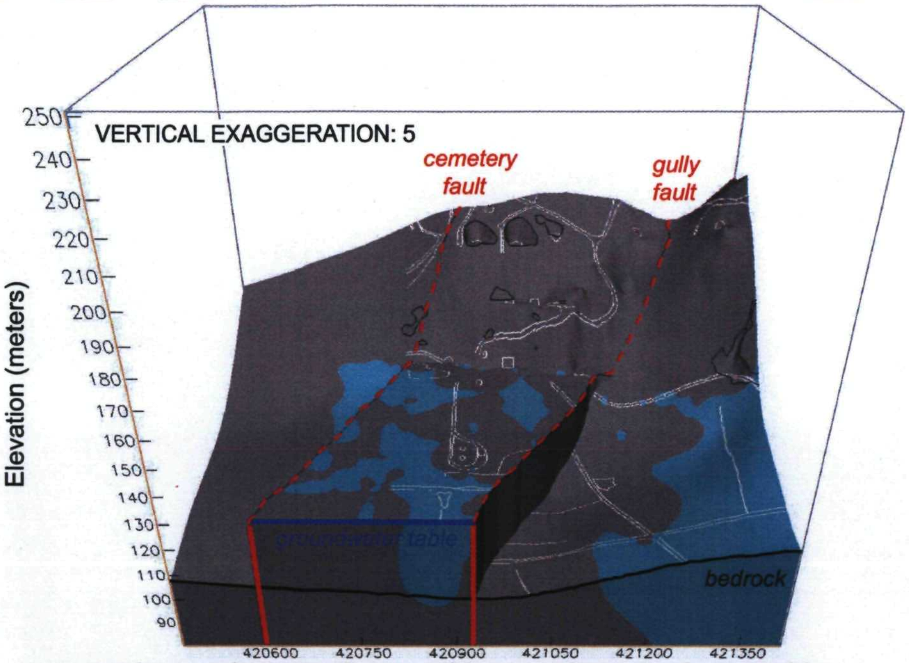
As seen on Profile 4, Profile 5 (Wenner array) contains a high resistivity signal suggestive of a deep permafrost layer that separates the alluvial and bedrock aquifers. The deep permafrost likely extends from about 300 to at least 400 m along the line. Again, no direct ground truth is available to support this interpretation, but area borehole AP-7946 shows a warm permafrost signal. It also appears that the last 30 m of the line could be getting into thicker, more massive permafrost based on the dipole–dipole model.

Profile 6

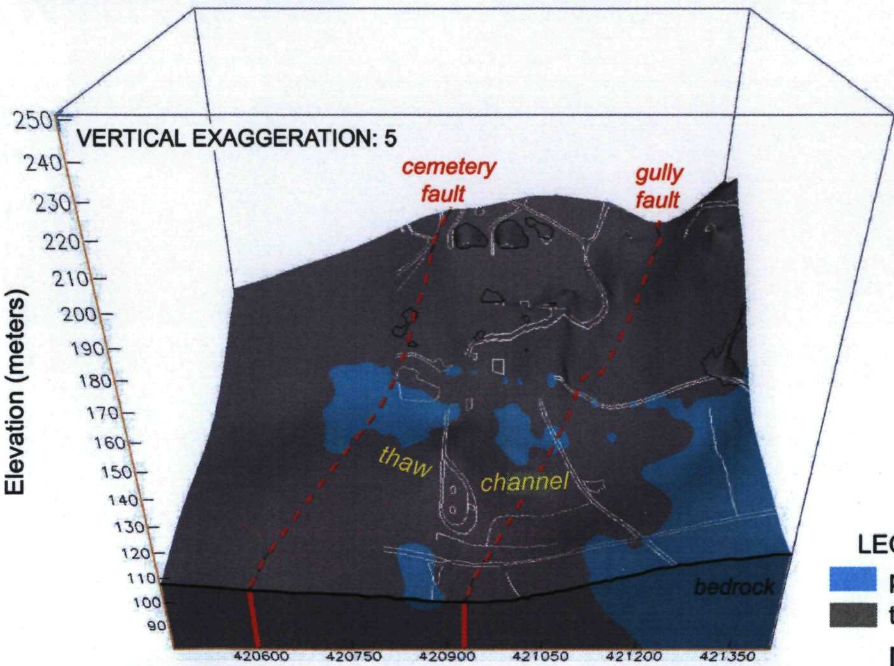
Profile 6 began at the south side of Lazelle Road, at the intersection with the Shannon Park Baptist Church driveway, near monitoring well UAFML3. The profile continued east along the south shoulder of Lazelle Road, across the base of Birch Hill, and through the gate at the east end of the Birch Hill Tank Farm. It ended at 850 m, just west of the quarry.

This profile indicates permafrost from 95 to 155 m, 220 to 265 m, 285 to 315 m (shallow), 330 to 345 m, 395 to 425 m, and discontinuous permafrost from 575 m to the end of the line (Fig. 9a). Drilling in this area has always indicated thaw; however, with the exception of the recently installed multilevel well AP-8784, none of the wells are deep, which is where the resistivity picked up a permafrost signal. As with Profile 3, this area had previously been characterized as thawed in the modeling effort.

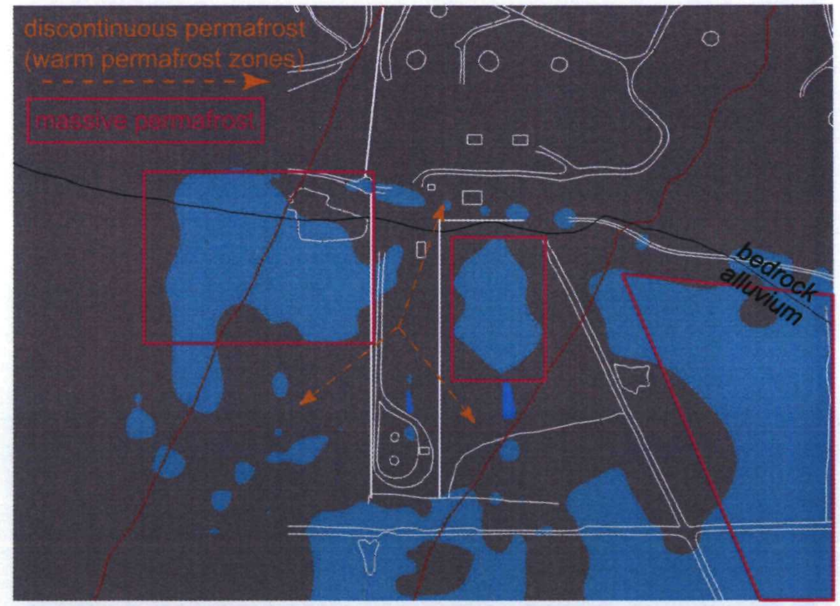
A deep high resistivity anomaly occurs at approximately 420 m. This anomaly appears similar to high resistivity anomalies on Profile 1 and 1999-Profile 15. It is also in the vicinity of the original pump house building, which was relocated higher on Birch Hill in the late 1950s because of problems related to the presence of permafrost. These three lines of evidence support the presence of a relatively large permafrost body at the base of Birch Hill. Also, Profile 6 shows three additional areas containing high resistivities at the base of Birch Hill. This suggests that permafrost is more persistent across the base of Birch Hill than previously thought. The significant ice bodies on Profile 6 at the base of the Tank Farm were added to the updated permafrost model (Fig. 10, cross section A, Fig. 11).



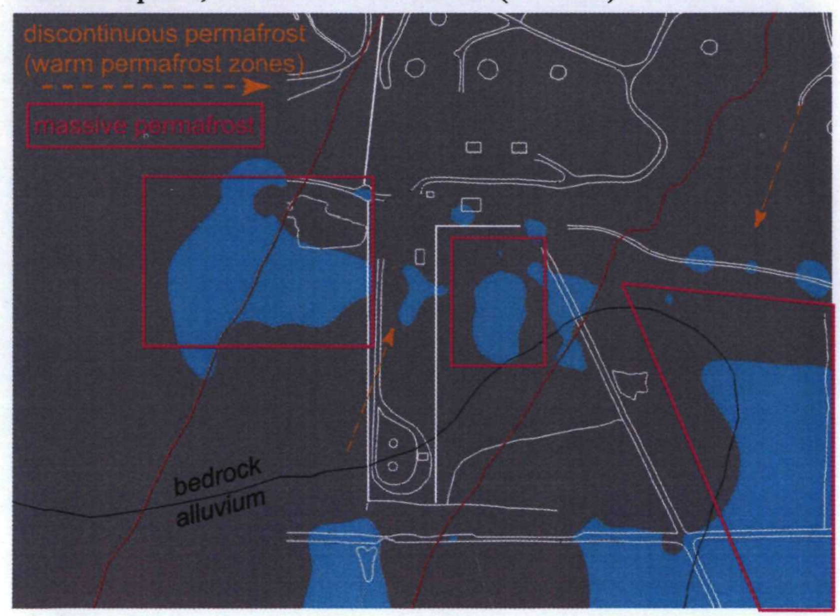
a. permafrost at the groundwater table, note the groundwater table is relatively flat and is not well defined east of the Gully Fault or West of the Cemetery Fault



b. permafrost at the bedrock-alluvial interface, note the irregular topography and large permafrost free areas to the south of the base of Birch Hill



c. occurances of both massive and discontinuous permafrost in the alluvial aquifer, elevation 126.5 meters (415 feet)



LEGEND
permafrost
thaw

d. occurances of both massive and discontinuous permafrost in the bedrock aquifer, elevation 113 meters (371 feet)

Birch Hill Resistivity Report	Figure 11 Permafrost Model at the Groundwater Table and Bedrock-Alluvial Interface, Selected Map Views	CRREL Opalia ENVIRONMENTAL LLC

DISCUSSION

Discontinuous permafrost

Several areas in OU3 have small-scale permafrost discontinuities (or more simply relatively small permafrost bodies) that would facilitate the transmission of water. Identification of these intermittent permafrost zones has been difficult because such zones are typically identified only when a borehole contains permafrost lenses. One-dimensional resistivity techniques (such as those used in 1999) alone may not reveal the presence of these areas and cannot define their extent. Although recent two-dimensional resistivity surveys have allowed location and mapping of these areas with greater certainty (Fig. 11), the linear nature of the resistivity profiles makes defining the lateral extent of these features difficult.

Thaw channel

Initial interpretations assumed that significant thaw was present beneath the Thaw Channel, based on the depositional history of this feature. As the Chena River migrated laterally across the OU3 area, it would have thawed the permafrost to some depth below the bottom of the channel. As the river continued to migrate and abandoned the Thaw Channel, some of the thawed areas could freeze again, creating discontinuous permafrost. Geophysical surveys (conducted in 1999 and 2004) allowed CRREL to confirm the thermal state of the Thaw Channel feature. It is frozen on the western side of Bentley Trust in an area with thick permafrost; the remaining extent of the Thaw Channel on Bentley Trust is thawed but surrounded by permafrost bodies of varying thickness. The Thaw Channel remains mostly thawed from the base boundary to Canol Road, and appears to be frozen again to the east of Canol Road in another area containing thick permafrost.

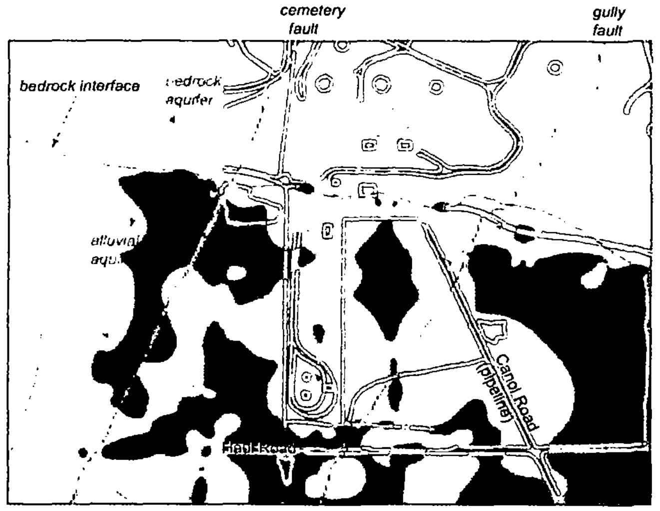
Permafrost in cleared areas

According to the results of the 2004 resistivity survey, there is intermittent permafrost present in both the alluvial and bedrock aquifers. Permafrost lenses present in the northern end of the Truck Fill Stand and at the base of Birch Hill have the potential to influence groundwater flow and contaminant migration. Recent analysis of aerial photos revealed that the northern end of the Truck Fill Stand near the base of Birch Hill was not cleared completely until the early 1970s, which is later then originally thought. Also, a review of historical documents recently recovered from the National Archives describes extensive permafrost at the base of Birch Hill underlying the original pump house. It was the presence of this permafrost that prompted the relocation of the pump house to Birch Hill. Therefore, it is not surprising to see significant permafrost lenses present in both of these parts of the site. Figure 12 shows the permafrost distribution at multiple elevations. These snapshots suggest that permafrost was quite extensive at the base of Birch Hill before it was disturbed.

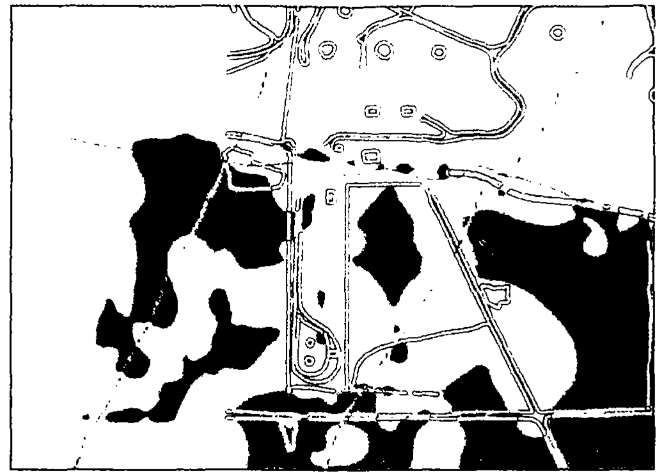
Vertical layering of intermittent permafrost

The areas where vertical layering of intermittent permafrost was suggested correspond to areas that have degrading permafrost, presumably at or near 0°C. The assumption that these areas contain warm permafrost is based on

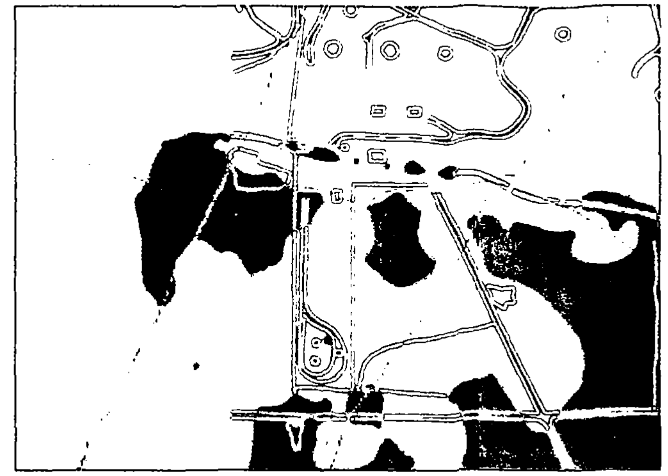
- the discontinuous and layered nature of the resistivity signals,
- the high degree of anthropogenic disturbances in these areas,
- the presence of boreholes that show variation between well and poorly bonded permafrost, and
- the presence of boreholes that have local lenses of frozen and thawed materials within their vertical extent.



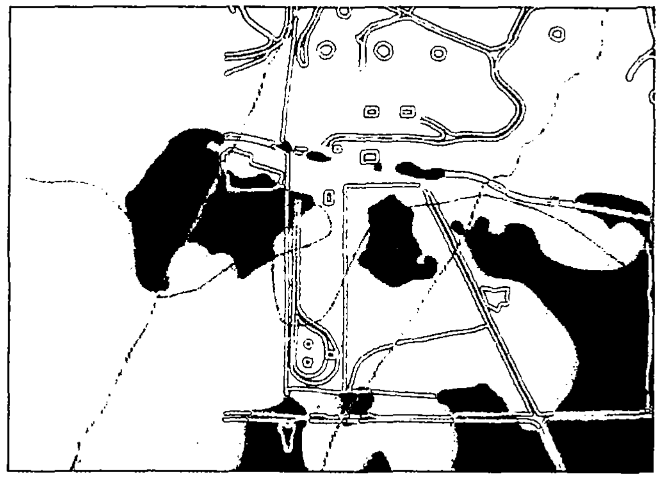
a. 131 meter (430 foot) elevation (13 foot depth): approximate elevation of the groundwater table, permafrost is extensive at the groundwater table.



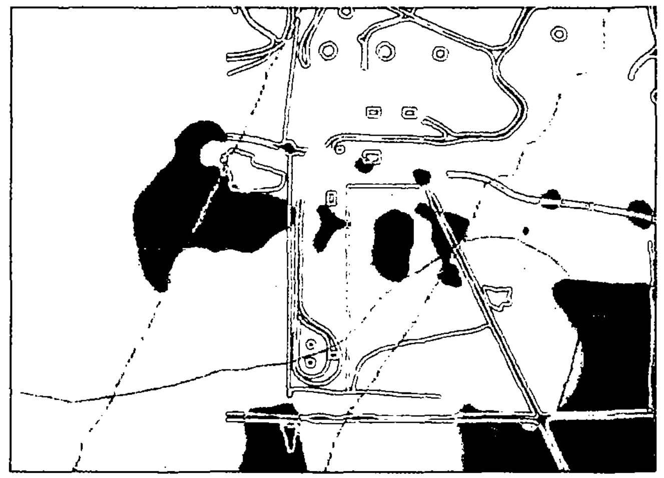
b. 128 meter (420 foot) elevation (23 foot depth): alluvial aquifer is starting to open up. Lenses of sporadic permafrost apparent at the base of Birch Hill and in the Truck Fill Stand. Irregularity in the warm areas (under the Canol Pipeline north of the Haul Road, south of the thaw channel).



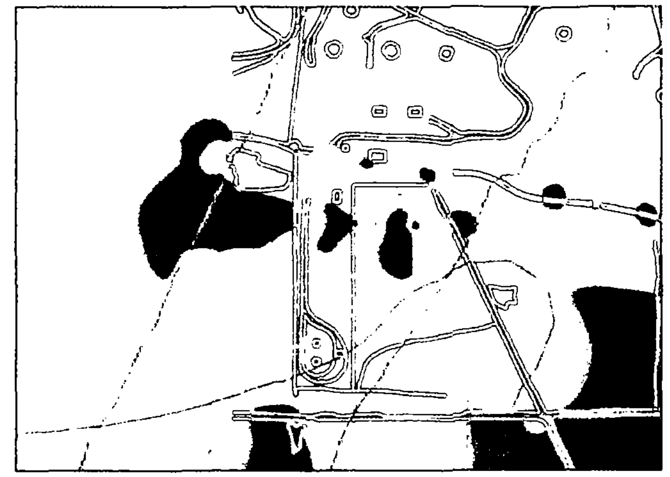
c. 123.5 meter (405 foot) elevation (38 foot depth): alluvial aquifer opens up.



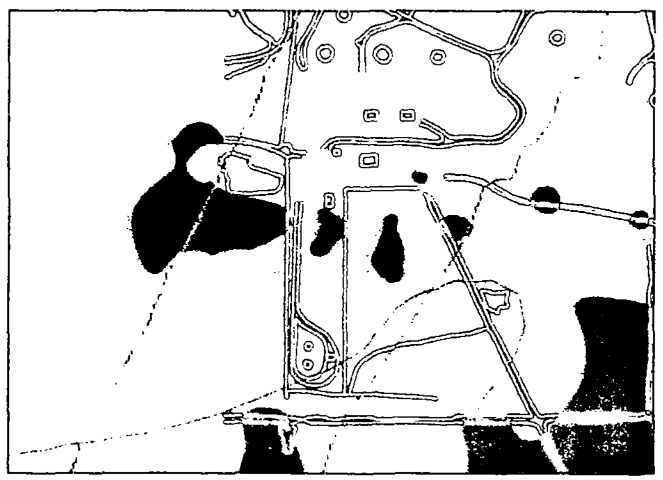
d. 120.5 meter (395 foot) elevation (48 foot depth): alluvial aquifer remains open.



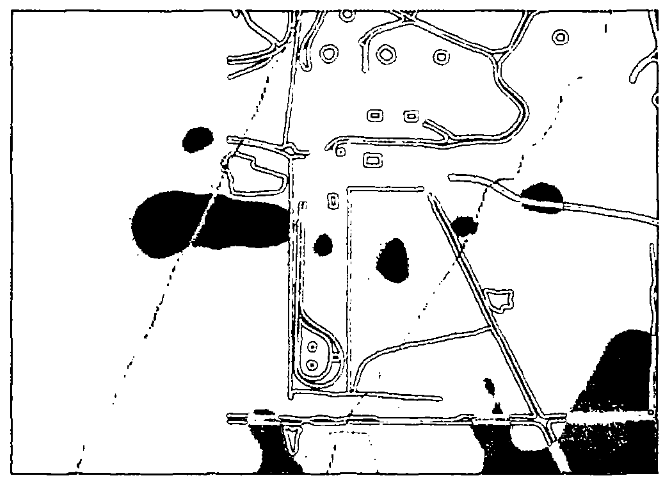
e. 113 meter (371 foot) elevation (72 foot depth): significant irregularities in warm permafrost area underlying the Canol Pipeline. Note this is the area Spring 2005 well cluster is going to be placed in.



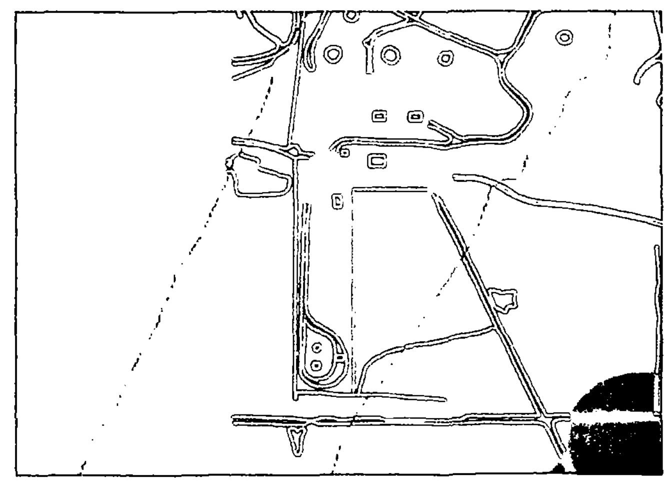
f. 110 meter (361 foot) elevation (82 foot depth): there are a series of permafrost bodies across the base of the hill suggesting permafrost was more extensive in this area historically.



g. 108 meter (354 foot) elevation (89 foot depth)



h. 101 meter (331 foot) elevation (111 foot depth): note linearity in permafrost, this is a result of the limited, primarily geophysical input available at depth.



i. 81.5 meter (267 foot) elevation (175 foot depth): permafrost appears to be completely thawed at depth.

LEGEND
permafrost
thaw

Birch Hill Resistivity Report	Figure 12 Permafrost Model Snap Shots	CRREL Opala

AP-7946 is located on Bentley Trust property near a well-used dirt trail. It shows three frozen zones separated by thaw. The thawed areas are composed of poorly graded sand and poorly graded gravel with sand. The frozen sections are composed of silty sand, well-graded gravel with sand, or well-graded gravel with silt. This follows the theory that cleaner sediments, with little to no fines, will thaw faster than sediments with a significant fine content.

The areas characterized by warm permafrost are south of the thaw channel on both the east and west side of the Truck Fill Stand, where layered resistivity signals were observed on Profiles 4 and 5, and between the massive permafrost on the north end of Profile 4 and Canol Road. Figure 13 shows a series of 3D snapshots of the layered permafrost model. South of the thaw channel the model shows extensive permafrost in both the alluvial and bedrock aquifers with a large area of thaw between them (12 m/40 ft thick). It does appear that the deeper layers do not completely limit communication between the bedrock and alluvial aquifers (i.e., in the large area with the layered signal, only part is frozen at the bedrock/alluvial interface). This supports the idea that the permafrost-free parts of the thaw channel are the most likely to see vertical contaminant migration, since the permafrost distribution may be fairly complex at depth elsewhere throughout the site.

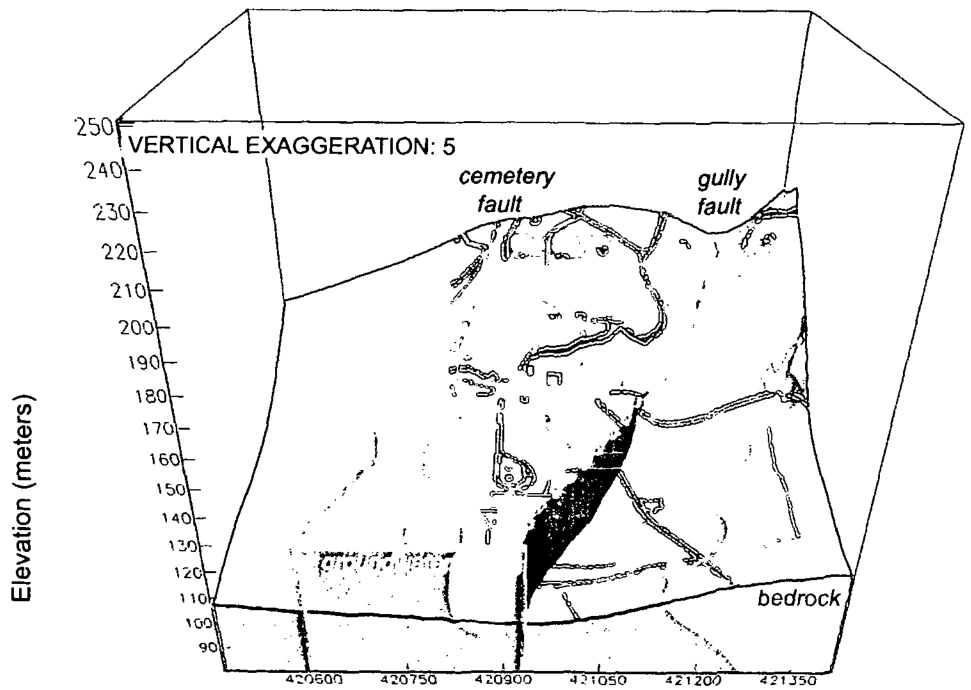
Massive permafrost

There is a massive block of permafrost present at the base of Birch Hill located almost entirely on the Bentley Trust property. It extends 225 m (738 ft) east to west across the post boundary and is between 50 and 60 m (131 to 164 ft) thick (Fig. 11). This area is currently mostly forested and relatively undisturbed. Clearing and subsequent development of this area would likely result in an increase in surface temperature, leading to permafrost degradation.

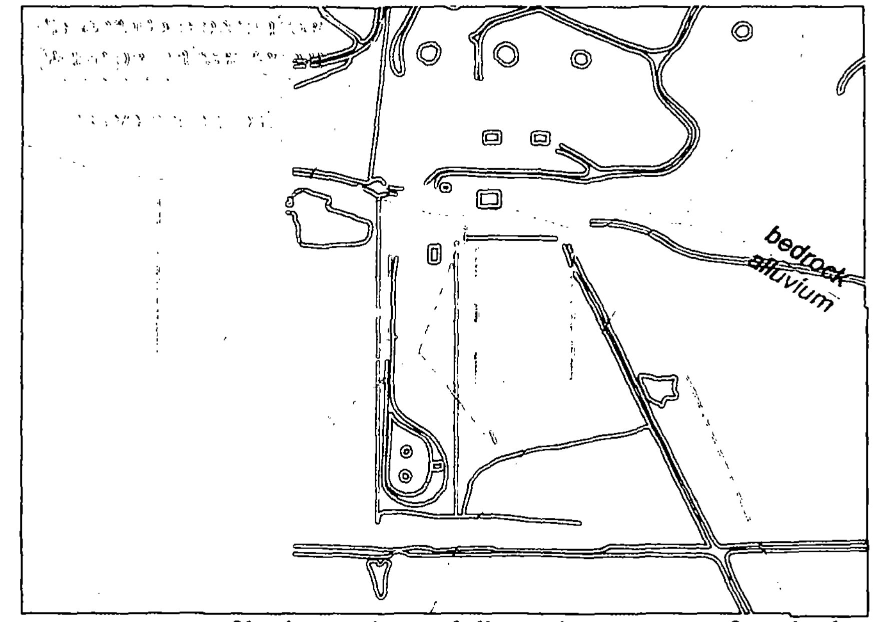
Another massive block of permafrost between the northern Truck Fill Stand and Canol Road extends to depths of 30 to 50 m (98 to 131 ft) (Fig. 11 and 12).

Thermal state of key bedrock structures

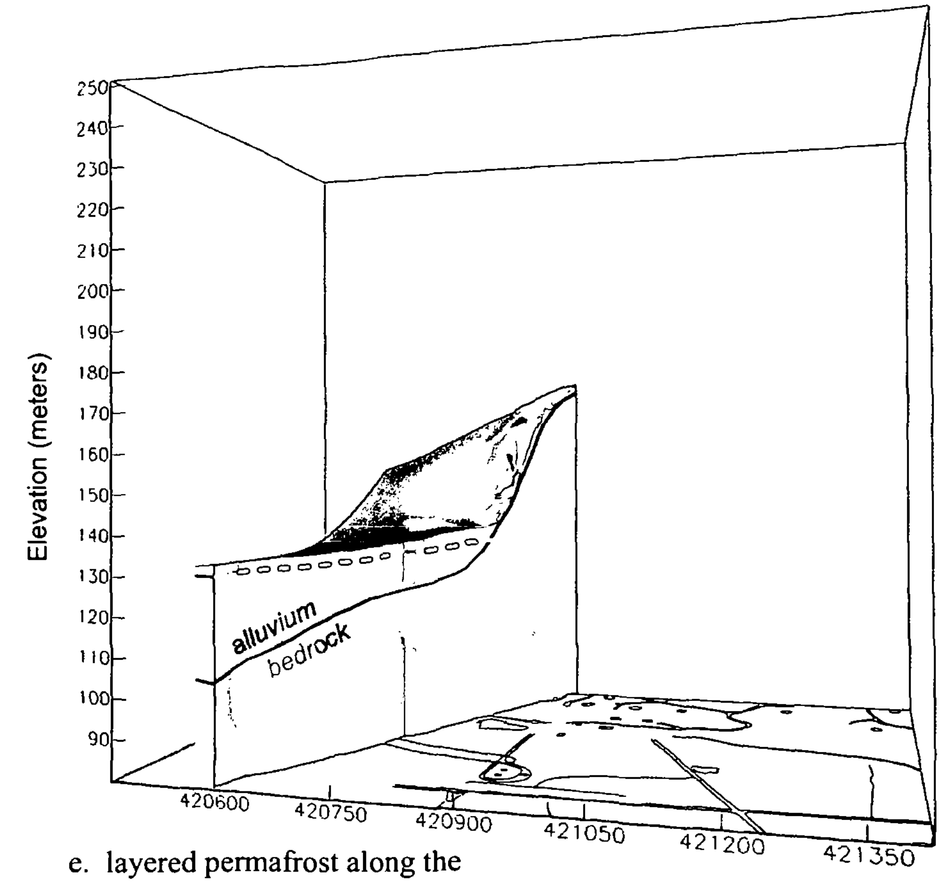
The Cemetery Fault trace is frozen at the base of Birch Hill as it passes through the massive permafrost zone on Bentley Trust. The Gully and Contact Fault traces are partially frozen at the base of Birch Hill. Permafrost is present at the bedrock interface in the vicinity of both of these features (Fig. 14).



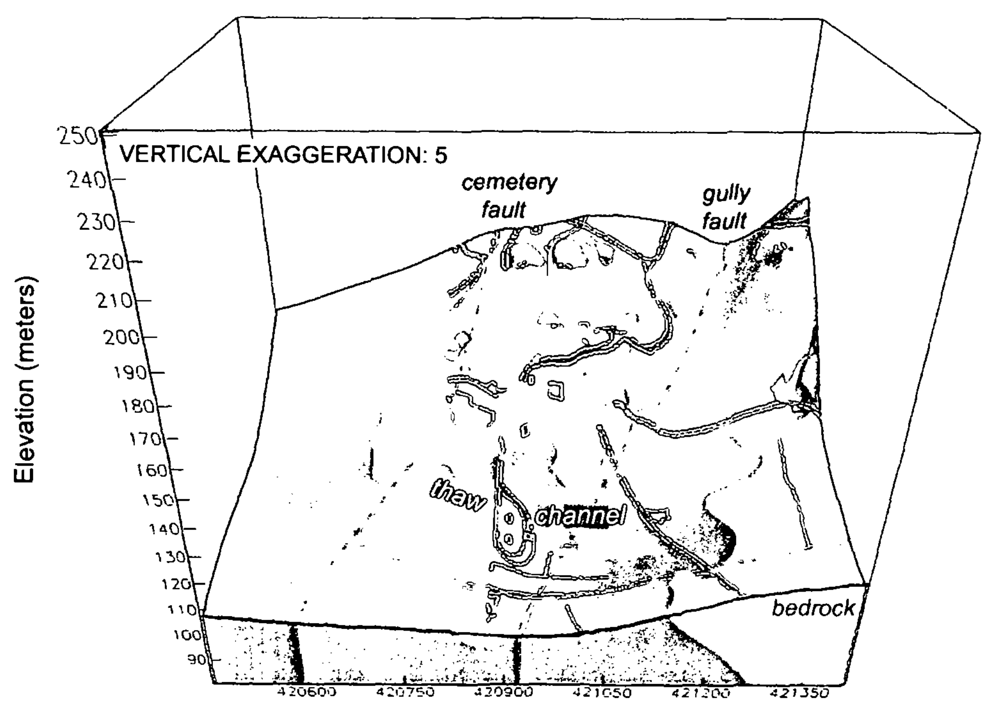
a. layered permafrost at the groundwater table, note the groundwater table is relatively flat and is not well defined east of the Gully Fault or West of the Cemetery Fault



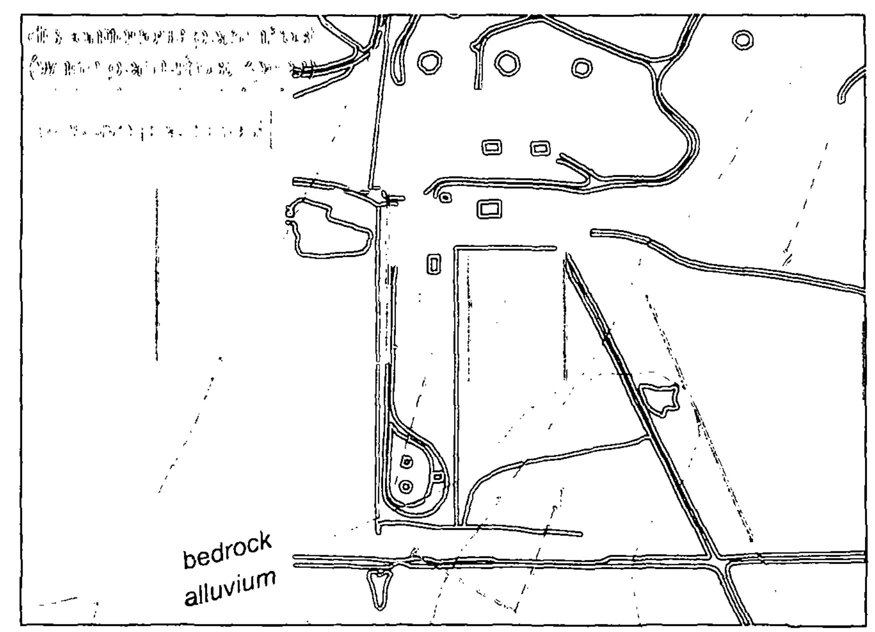
c. occurances of both massive and discontinuous permafrost in the alluvial aquifer, elevation 129.5 meters (425 feet)



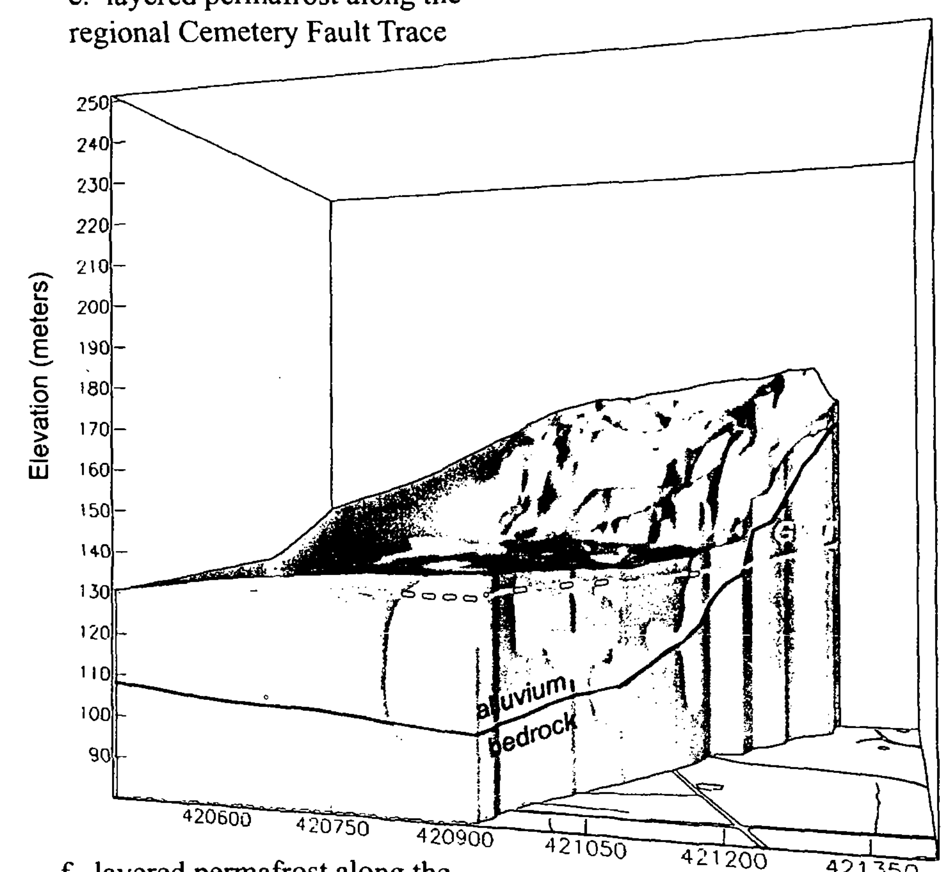
e. layered permafrost along the regional Cemetery Fault Trace



b. layered permafrost at the bedrock-alluvial interface, note the irregular topography and large permafrost free areas to the south of the base of Birch Hill



d. occurances of both massive and discontinuous permafrost in the bedrock aquifer, elevation 108.5 meters (356 feet)



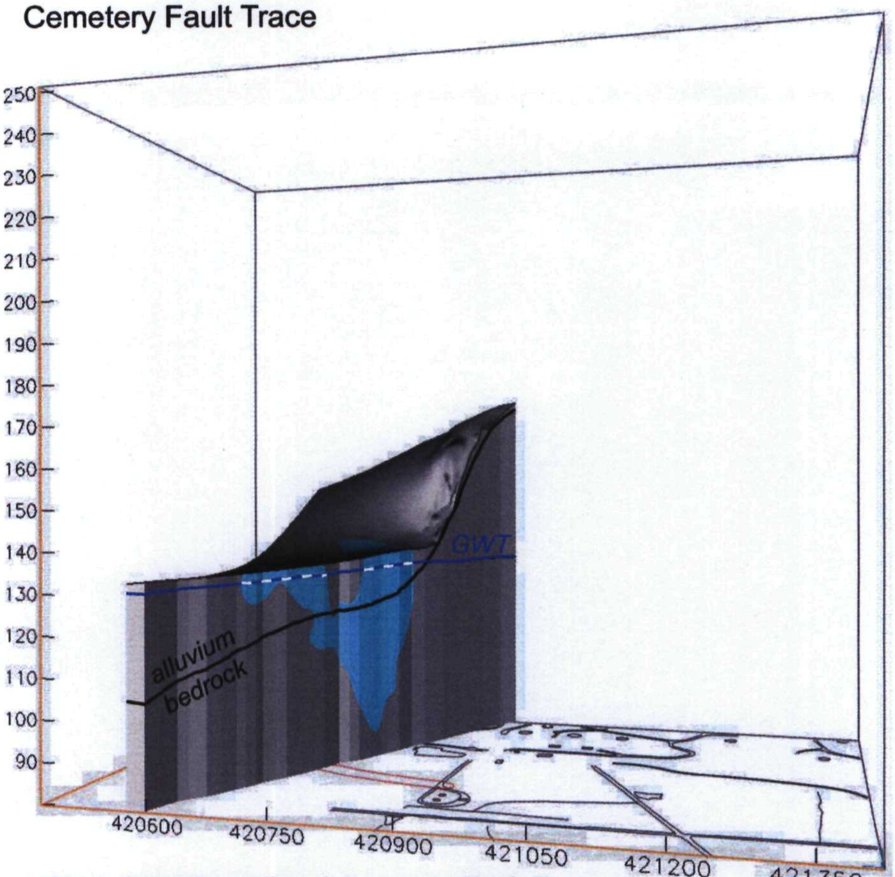
f. layered permafrost along the regional Gually Fault Trace

LEGEND

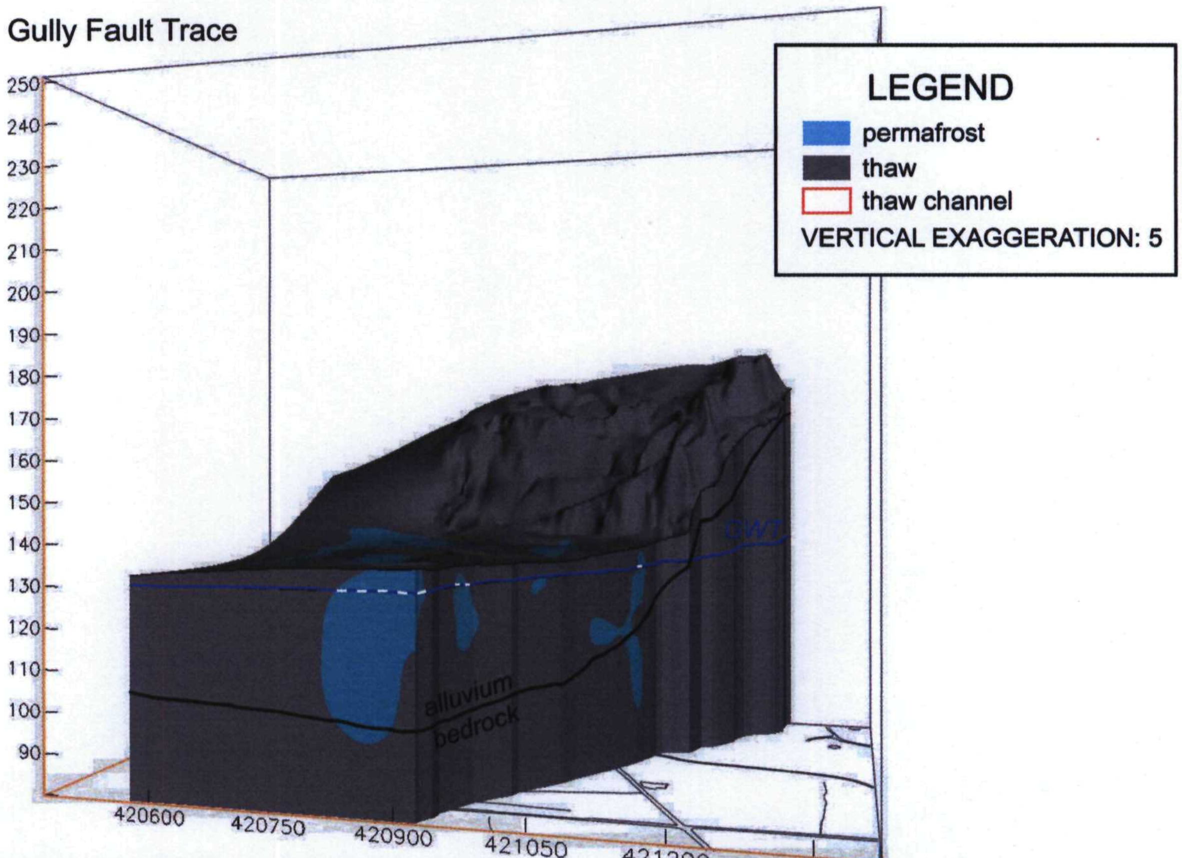
- permafrost
- thaw
- thaw channel

VERTICAL EXAGGERATION: 5

Birch Hill Resistivity Report	Figure 13 Layered Permafrost Model at the Groundwater Table and Bedrock- Alluvial Interface, Selected Map Views	CRREL Opalia Environmental LLC



a. permafrost along the regional Cemetery Fault Trace



b. permafrost along the regional Gually Fault Trace

Birch Hill Resistivity Report	Figure 14 Permafrost Distribution in the Regional Cemetery and Gully Fault Traces	CRREL Opalia ENVIRONMENTAL LLC

Depth of thaw beneath anthropogenic features

Permafrost analyses have been focused on the occurrence of permafrost below the groundwater table. However, some observations have been made regarding the degree of thaw under anthropogenic features, such as Canol Road and the Canol pipeline, in the unsaturated zone. Resistivity data indicate a deep thaw below the Canol pipeline, possibly due to heat flux from the relatively warm fuels in the pipeline to the surrounding alluvium, and a high level of disturbance during pipeline construction. In contrast, only shallow thaw was found below Canol Road and the Haul Road. This result was unexpected as it was hypothesized that areas cleared for long periods would thaw over a decade or two. The gravel fill on the Haul Road and Canol Road surface may insulate the permafrost below to some degree from summer temperatures and allow for greater convection in the winter months. The presence of snow will insulate the ground during the winter and reduce convection, leading to warmer surface ground temperatures. Therefore, areas where snow is removed in the winter, such as Canol Road, would be expected to have a lower winter ground surface temperature than surrounding areas with significant snowpack. These theories explain why permafrost is persistent along much of Canol Road and the Haul Road.

Permafrost on Bentley Trust

Permafrost on Bentley Trust can be grouped into three categories: massive, intermittent shallow, and deep. The massive permafrost at the base of Birch Hill extends from just below the organic layer to as deep as 60 m (164 ft). This permafrost covers an area of no more then 8 acres. AP-6559 was drilled into the massive permafrost. The top 4 m (13 ft) of this boring are logged as frozen silts and sands with as much as 97% fines. The massive permafrost area on Bentley Trust would not be thaw-stable where this thick silt layer is present.

The intermittent, shallow permafrost is located south of the massive permafrost starting at 170 m (see Profile 5, Fig. 9b). This permafrost extends from just below the ground surface to approximately 5–10 m below the groundwater table. This permafrost may have some impact on groundwater flow, but does not extend far into the saturated aquifer.

A deep resistivity anomaly is observed on Profile 5 from 300 to 400 m and on Profile 2 from 535 to 765 m on the Wenner array data. Deep permafrost within the bedrock was interpreted from this high resistivity signal. There are no boreholes in this area that extend deep enough to groundtruth the anomaly. Given the sharp contrast in resistivity, it is assumed that a relatively thin layer of permafrost persists within the bedrock or a change in bedrock stratigraphy occurs at this location. Because groundwater can flow above this anomaly, whether it is permafrost or a change in bedrock type may not affect the overall groundwater flow patterns at the site. A similar anomaly is seen at the south end of Profile 4. Contaminants encountered historically are at depths that suggest contamination is introduced above this anomaly.

CONCLUSIONS

Permafrost is an impermeable boundary to groundwater flow, influencing aquifer configuration and communication between the alluvial and bedrock aquifers. Discontinuous permafrost creates a semi-permeable boundary that could permit contaminant transport.

The recent two-dimensional resistivity survey and analysis revealed an even more complex permafrost distribution than previously defined. The most notable trends resolved in the resistivity analyses are as follows:

- the resistivity of permafrost is generally 2–8 times that of the surrounding thawed materials at OU3;

- there is a more extensive site-wide presence of discontinuous permafrost, including a potential vertical layering of frozen and thawed ground and the presence of intermittent permafrost in cleared areas (i.e., the truck fill stand and the base of Birch Hill) previously believed to be almost completely thawed;

- the depths of massive blocks of permafrost previously undefined;

- the thermal state of key bedrock structures recently identified in the site seismic survey/geologic modeling effort;

- the depth of thaw below certain anthropogenic features such as the Canol Pipeline; and

- the regional Gully and Cemetery Faults do not have resistivity anomalies associated with them that would allow the faults to be traced in the subsurface.

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APPENDIX A

APPENDIX A

Permafrost Model Evolution, Fort Wainwright, Fairbanks Alaska – Technical Memorandum

To: Beth Astley/CRREL

From: Colby Snyder/Opalia Environmental

Date: March 2005

INTRODUCTION

This technical memorandum describes the development of the permafrost distribution and aquifer configuration model for Operable Units 3 and 4 (i.e., the areas north of the Chena River, including the Birch Hill Tank Farm site) at Fort Wainwright, located in Fairbanks Alaska. The preliminary model was developed in October 1998 and has undergone several revisions; the last update was completed in March 2005. The permafrost/aquifer model was incorporated in to the Birch Hill Geologic Model which includes regional and local structures; however, this memorandum focuses solely on the development of the permafrost and aquifer distribution model.

Site permafrost and bounding features

Permafrost is perennially frozen ground that occurs wherever mean annual temperatures remain at or below freezing for two or more years. It is present in the Fairbanks area because of the region's sub-arctic climate, which has a mean annual temperature around -2.9°C. The uppermost layer of ground, or the "active layer", undergoes seasonal freezing and thawing, whereas much of the material below the active layer remains frozen throughout the year. In Fairbanks, the average depth of the active layer is 1 to 2 meters, but can be as small as a few centimeters where massive permafrost is present.

The spatial complexity of the permafrost at this site reflects past geologic events, including relocation of the meandering river channels, degradation associated with saturated groundwater flow, climatic events, and surface disturbances, such as from human activity. Thick organic layers insulate permafrost and prevent or slow its degradation. Anthropogenic disturbances, such as excavation and construction, as well as conductive heat flux from groundwater flow, generally degrade permafrost. Permafrost also tends to be absent under deep water bodies and the incidence angle of solar radiation causes permafrost to be absent on south-facing slopes.

Permafrost is expected to be absent under bounding site features such as the Chena River (a deep water body), the Tank Farm on Birch Hill (a south facing slope) and under the Steese Highway (a major regional roadway). The permafrost model is bounded by the Chena River to the south, the Tank Farm to the north and the Steese Highway to the west (Fig. A-1). The eastern boundary is Ski Road, it is not a geologic or anthropogenic feature, it is simply where the borehole input ends. There is a separate model that covers the milepost sites further east (Fig. A-1).

Groundwater Aquifers

At OU3, previous borehole and GPR data show that three separate groundwater aquifers occur due to the presence of permafrost. A supra-permafrost aquifer may develop above the permafrost; a confined or semi-confined sub-permafrost aquifer may be found below the permafrost and an intra-permafrost aquifer occurs where free water is found within permafrost (Main Report Fig. 2). These permafrost aquifers occur primarily in the alluvial aquifer except between the base of Birch Hill and the Haul Road where permafrost is present to varying degrees in the bedrock. The depth to groundwater ranges from 3 to 5 meters within the study area.

MODELING HISTORY

Preliminary Model

In October of 1998 CRREL was tasked with determining if a complex geologic model (specifically the permafrost distribution and subsequent aquifer configuration) could be developed and provided electronically to CH2M Hill for use in the site groundwater flow and contaminant transport model.

A numeric model of the three-dimensional permafrost and aquifer distribution was successfully developed, exported and incorporated into the CH2M Hill site groundwater flow and contaminant transport model (see Preliminary Model of Permafrost and Aquifer Distribution in Part of OU3, FWA, Alaska. Preliminary Model and Explanatory Draft Report. Lawson, 1998).

Once it was determined that the geologic and groundwater models could be interfaced significant data gaps had to be filled before a suitable permafrost/aquifer model could be generated. The data limitations at the time included a lack of input at depth and a lateral distribution of boreholes that was too coarse to resolve exact permafrost/thaw boundaries.

Model Iteration #1

In 1999 an extensive 1-dimensional resistivity survey was undertaken at the Birch Hill Tank Farm site and adjacent Bentley Trust Property. The results were incorporated in to the permafrost model and are summarized below. A discussion of the complete investigation can be found in the CRREL Report: A Summary of Current Hydrogeologic Investigations of the Birch Hill Tank Farm and Truck Fill Stand, OU3, FWA (Astley et al, 1999).

From March to September 1999 a geophysical investigation, including DC Resistivity and ground penetrating radar (GPR), was conducted in OU3 to define lateral changes in stratigraphy, locate fractures and delineate permafrost boundaries (Astley et al, 1999). Permanently frozen materials offer greater resistance than the same materials in an unfrozen state making permafrost relatively easy to identify with DC Resistivity. Sixtythree profiles and 20 soundings were collected along previously established GPR lines, roads and through wooded areas that had not previously been studied using geophysics. Eighteen of the profiles were collected on Bentley Trust and 25 in and around the Truck Fill Stand. Typically, several profiles were collected on the same transect to try and identify changes in the permafrost distribution with depth.

This resistivity analysis has shown that permafrost is indicated by resistivity values ranging from 1,000 to 18,000 ohm-meters. Profiles that indicated permafrost were re-formatted to be used as input for the permafrost/aquifer model. The input was in the form of data lines (Fig. A-2). Since several profiles were typically collected along a single line the input was stacked, meaning there were 2 to three lines of input per resistivity profile (Fig. A-2).

This iteration was a great improvement over the preliminary model because the resistivity coverage allowed more complete definition of permafrost/thaw boundaries laterally; it also revealed that the western edge of the thaw channel is actually frozen. The model at depth was also improved with this iteration however; complete vertical characterization of massive permafrost blocks was not achieved. In addition, limited borehole data was available to ground truth the resistivity data collected on Bentley Trust and as a result the interpretations and subsequent model input were based on observations made on site profiles that had associated ground truth data.

Model Iteration #2

In October 2002 the model was revised a second time to include data from newly acquired boreholes, 23 in total, collected at the site and on the adjacent Bentley Trust property. Of the 23 boreholes 5 were located on Bentley Trust (AP-7946, AP-7947, AP-AP-7948, AP-7950, and AP-7951) and 4 were in the Truck Fill Stand (AP-7844, AP-7845, AP-7846 and AP-7847), the remaining wells were on Birch Hill where permafrost is absent. Three of the Bentley Trust wells encountered permafrost (AP-7946, AP-7950 and AP-7951) and therefore provided ground truth for the 1999 resistivity based permafrost interpretations. AP-7847 in the northern end of the Truck Fill Stand also encountered permafrost; but the extent of permafrost was not logged and could not be used as model input. AP-7847 is co-located with AP-6583 which also has permafrost and was already included in the model input. The complete summary of this revised analysis can be found in the CRREL Technical Memorandum – Aquifer and Permafrost Model Update, FWA (Snyder, 2002), the key findings are noted below.

The new ground truth data confirmed the resistivity interpretations made on the alluvial sections of the Bentley Trust profiles were accurate. However, interpretations of the permafrost extent in the bedrock on these profiles had to be modified.

In addition to refining the permafrost distribution in the bedrock, the resistivity data was re-evaluated to determine the extent of intermittent permafrost at the site. Intermittent permafrost is defined as small-scale permafrost discontinuities (alternating permafrost and thaw on a local scale) that would facilitate the transmission of water. Typically intermittent permafrost is associated with zones of warm (degrading) permafrost and has lower overall resistivity values.

The model input for this iteration included the new borehole data as well as the refined line input from the 1999 resistivity surveys.

Permafrost was clearly less persistent in the bedrock west of the site in model iteration #2. Areas of intermittent permafrost were identified but the extents were uncertain because of the nature of the 1-dimensional resistivity input. This iteration still lacked resolution of the depth of the massive permafrost blocks identified in the 1999 investigation.

Model Iteration #3
In June 2004 6 two-dimensional resistivity profiles were collected at this site and on the neighboring Bentley Trust property. Between 1999 and 2004 significant advances in resistivity were made. The methods used in the 2004 survey allowed CRREL to conduct a more refined survey with improved ability to discern local-scale permafrost features as well as allowing greater depth penetration.

The 2-dimensional resistivity cross section inversions were incorporated in to the permafrost model input data set. The input is still linear in nature but provides a 2-dimensional depiction of the permafrost distribution along each profile (Fig. A-2).

The resulting analysis largely supported the modeled permafrost distribution where the new data was co-located with existing information. This survey also filled some significant data gaps, specifically:

- resolving the maximum depth of massive permafrost bodies present at this site,
- defining intermittent permafrost zones in areas previously thought to be permafrost free, and
- providing additional insight in to the nature and extent of intermittent (warm) permafrost in areas already defined as such.

At the time of this memo, the 2004/2005 model represents the final site permafrost model iteration.

The results of this analysis can be found in the Operable Unit 3 Resistivity Investigation, FWA (Astley, 2005).

METHODS

The software selected to generate the permafrost/aquifer distribution model was Dynamic Graphics EarthVision software. EarthVision is an integrated software system used by earth science professionals to visually analyze data, create descriptive models based on that data, and perform visual and numeric analysis in both 2- and 3-dimensions.

EarthVision includes a minimum tension gridding (MTG) technique that can be used to model surfaces and volumes. This gridding method involves a phased approach that includes a weighted average calculation, followed by the application of a cubic function. The initial weighted average captures the underlying global trends in the data. The subsequent iterations use the cubic function to incorporate the local variation. The bedrock-alluvial interface and groundwater table were developed using 2-dimensional MTG and the permafrost distribution was developed using 3-dimensional MTG.

The available quantitative permafrost input data includes:

- Permafrost intercepts from site boreholes.
- Profiles containing higher resistivity values interpreted to be permafrost from the 1999 resistivity survey.
- Lines with bright lateral reflectors interpreted to be permafrost from GPR surveys.
- Cross-sections of higher resistivity values interpreted to be permafrost from the 2004 resistivity surveys.

Qualitative data, used to help confirm or refine the 3-dimensional model includes:

- the original CRREL 2-dimensional permafrost maps,
- a vegetation survey, and
- aerial photos.

The borehole input data set includes over 1,000 borings and monitoring wells installed between Birch Hill and the Chena River, with the densest set of boreholes found in the vicinity of the Tank Farm/Truck Fill Stand. Resistivity profiles are only available in this area. GPR data is found throughout the area north of the Chena River, but only the lines in the vicinity of the Tank Farm site were used as model input (Fig. A-1).

The initial permafrost model, as well as the first model iteration utilized an indicator data set for the permafrost. Frozen ground was assigned a value of +1 and thaw was assigned a value of -1, hence 0 was considered the permafrost/thaw boundary.

Subsequent model iterations also used an indicator data set; frozen ground was still assigned a value of +1, but now thaw has a value of 0. These indicator values resemble probabilities and can be used in that way. When an indicator value is greater then 0.5 it indicates a likely permafrost zone, values greater the 0.75 are most likely permafrost and anything greater then 0.9 is almost certainly permafrost. This approach allows the groundwater modeling team some flexibility in the assignment of the frozen (impermeable) / thaw (permeable) boundary during the groundwater model calibration process. It also, provides drillers with some additional information about where they will likely encounter permafrost versus where it is possible to encounter permafrost, etc.

It should be noted there are 3 permafrost models, the original (large-scale) model covers the area north or the Chena River extending to Ski Road, the revised (local/site-scale) model covers the Birch Hill Tank Farm site as well as the adjacent Bentley Trust property. The third model is of the permafrost configuration at the Milepost 2.7 and 3.0

sites (Fig. A-1). The borehole data is interrupted in between the Milepost sites and Ski Road so a continuous model is not possible. It should be noted that there is GPR data available in this area that could be quantified and the two models could then be combined.

The grid size for the large-scale model is 10 meters by 10 meters by 3 meters (32 feet by 32 feet by 10 feet). The grid size for the local, site-scale model is 5 meters by 5 meters by 1.5 meters (16 feet by 16 feet by 5 feet). The large-scale model includes the area represented by the site-scale model but is a lower resolution representation of permafrost there due to the larger grid size. The groundwater modeling team was provided both models and used the local model for the assignment of permafrost distribution at the site and the large-scale model for the surrounding areas. It would not be appropriate to use the smaller grid size for the large-scale model because we lack a dense set of input data in the areas surrounding the site. It would also greatly increase the processing times and associated file sizes.

The last step in the modeling process was to superimpose the permafrost distribution grid on the site stratigraphy, specifically, the ground surface, groundwater table, bedrock-alluvial interface and the regional structures.

PERMAFROST MODEL ACCURACY

The uncertainties are specific to the discrete models. The large-scale model is a reasonable generalization of the permafrost north of the Chena River, but can not accurately define local scale features such as thaw zones because of the limitations in the input data set and the large geographic model range. The site-scale model is an accurate representation of the permafrost at the Tank Farm site with localized data gaps. The milepost model is a preliminary model that does provide some insights in to the complexities of the permafrost distribution but is not able to resolve groundwater or contaminant flow pathways.

The uncertainty associated with the site-scale model is discussed in more detail below.

Site-Scale Model

Figure A-3 shows the residual model errors. Residuals are defined as the difference between the actual input data value and the value of the model at that point; essentially the residual errors indicate where the modeling technique is having trouble matching the input data set. The majority of the site has a very good model fit, but not surprisingly, the warm permafrost zones show the poorest model fits. A detailed discussion of the nature of the warm permafrost zones at this site can be found in the Birch Hill Permafrost Resistivity Investigation (Astley, 2005). In general, they are areas were the discontinuous nature of the permafrost is difficult to resolve. The modeling technique has trouble with the small scale variations in permafrost in these areas. It should be noted that the true shape of the intermittent permafrost in areas formerly modeled as permafrost free, (resolved in the 2004 resistivity survey), are still difficult to define 3-dimensionally due to the linear nature of the model input.

REMAINING DATA GAPS

Large-Scale Model

In general the data gaps are related to the use of the model. The input data for the majority of this model is limited to borehole data. It does show a reasonable representation of the global trends (for example that permafrost is frozen to bedrock over a large portion of the base of Birch Hill), but can not resolve the shape and extent of local features such as thaw channels near the landfill. It does help identify areas where the permafrost distribution is fairly complex even though it can not define the shape and extent of these areas. If there are specific areas that would benefit from definition of local scale features then a resistivity survey should be conducted.

Site-Scale Model

The data gaps here are associated primarily with the warm permafrost zones shown in Figure A3. In general, these areas are more permeable then the massive, cold permafrost but less permeable then the completely thawed areas. Resolution of the true shape and extent of the permafrost bodies in a warm/degrading permafrost zone would require a dense set of boreholes and even with this data are probably not resolvable.

Milepost Model

This model has an extremely localized input data set, meaning that there is very limited data surrounding the site on 3 sides. It could be greatly improved by incorporating the existing GPR data and could be as accurate as the site-scale model if a 2-dimensional resistivity survey was conducted because it is a relatively small area.

For additional information on the permafrost model contact Colby Snyder of Opalia Environmental LLC (csnyder@opaliaenv.com) or Beth Astley of CRREL (Beth.N.Astley@erdc.usace.army.mil).

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Astley, B., Snyder, C., Peapples, P., Lawson, D., Arcone, S., Delaney, A. (1999) A summary of current hydrogeologic investigations of the Birch Hill Tank Farm and Truck Fill Stand, Fort Wainwright, Alaska . December 1999. Prepared for U.S. Army Alaska, Directorate of Public Works. CRREL Summary Report.

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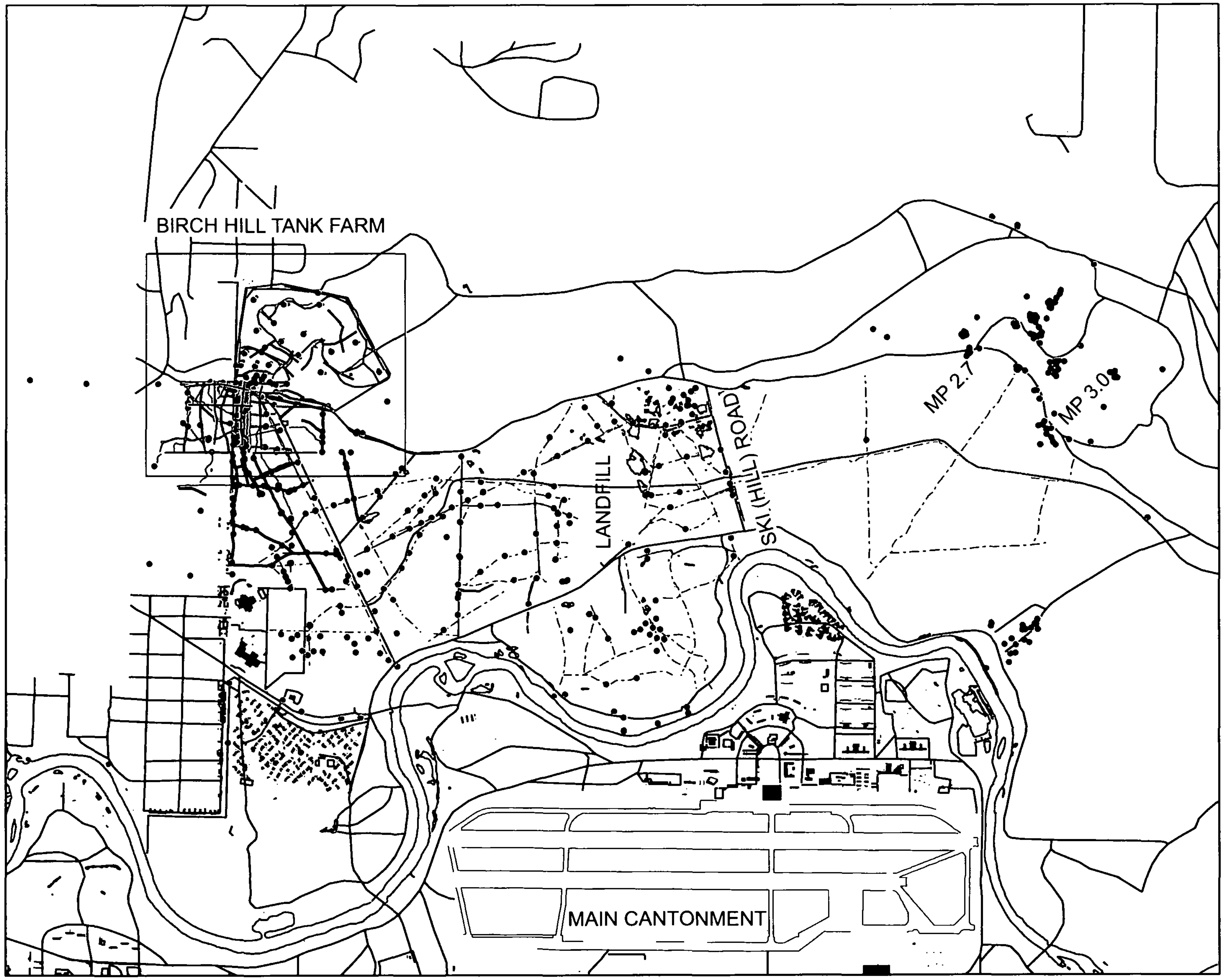
Lawson, D.E. and Snyder, C.P. (1998). Preliminary Model Permafrost and Aquifer Distribution in Part of OU3, Fort Wainwright, Alaska. Preliminary Model and Explanatory Draft Report. November.

Snyder, C., Kopczynski, S., Astley, B. (2003) Aquifer and Permafrost Model Updates, 1st Quarter 2003 Operable Unit 3 – Birch Hill Tank Farm and Truck Fill Stand, Fort Wainwright, Alaska. February 2003. Prepared for U.S. Army Alaska Directorate of Public Works, CRREL Technical Memorandum.



Basewide/Large Scale Model Input

Borehole/Well Input

● boring and well locations

Geophysical Input

1999 Resistivity Profiles

1999 GPR Line

2004 Resistivity Cross Section

Geophysical Data

1999 GPR Line

1993 to 1995 GPR Line

note: none of the 1993 to 1995 lines were used as model input, only some of the 1999 lines were used

0 0.25 0.5 1 Kilometers

0 0.15 0.3 0.6 Miles

Local/Site Scale Model Input

Borehole/Well Input

● boring and well locations

● bentley well locations (2001)

Geophysical Input

1999 Resistivity Profiles

1999 GPR Line

2004 Resistivity Cross Section

Geophysical Data

1999 GPR Line

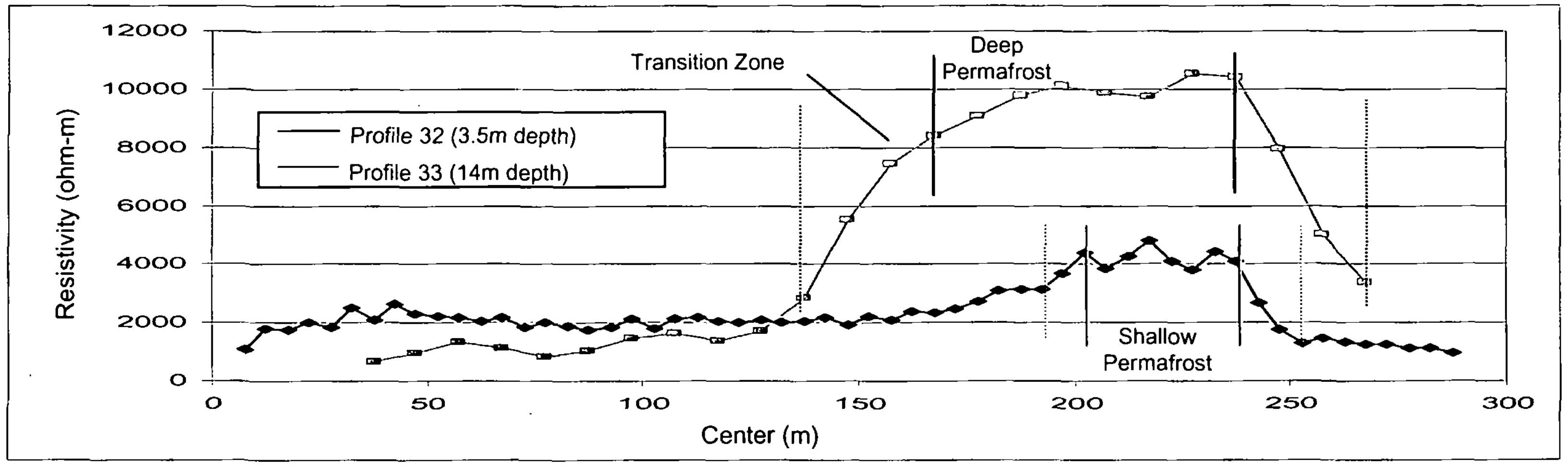
note: Not all the GPR lines were used as model input.

0 130 260 520 Meters

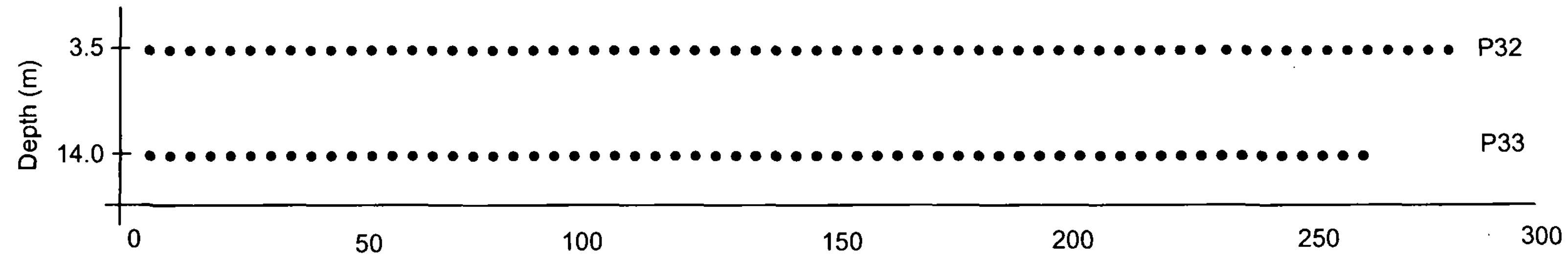
0 437.5 875 1,750 Feet

Birch Hill Resistivity Report	Figure A-1 Permafrost Model Input	CRREL Opalia Environmental LLC

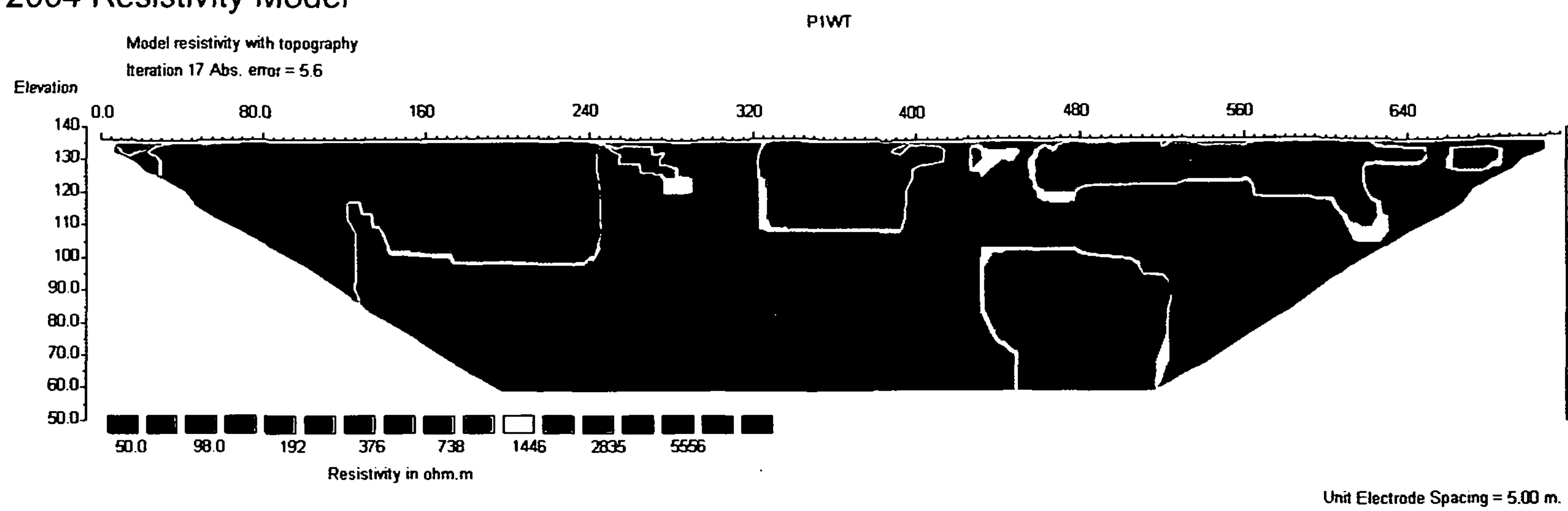
1999 Resistivity Profile



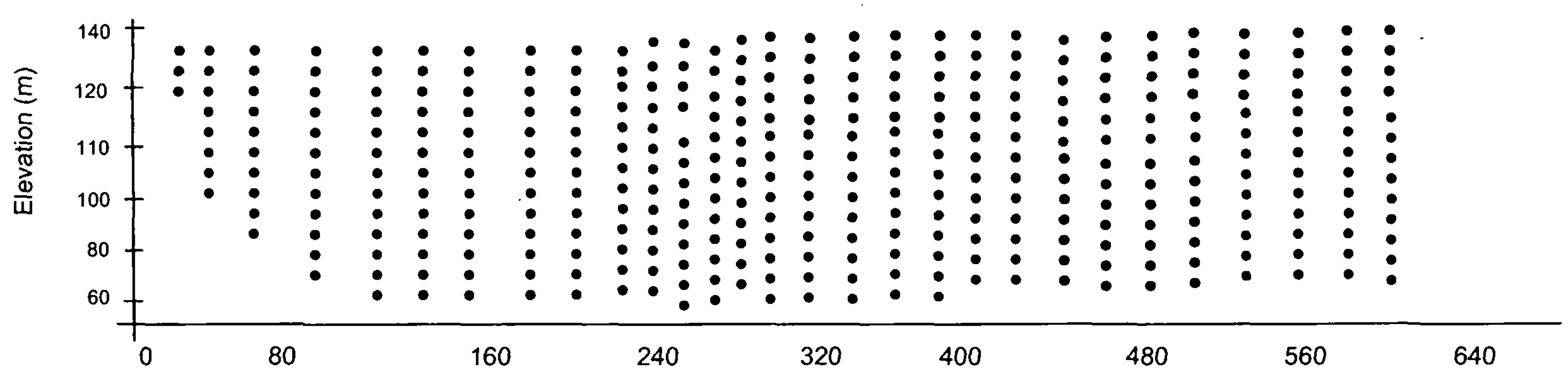
1999 Resistivity (line) Input



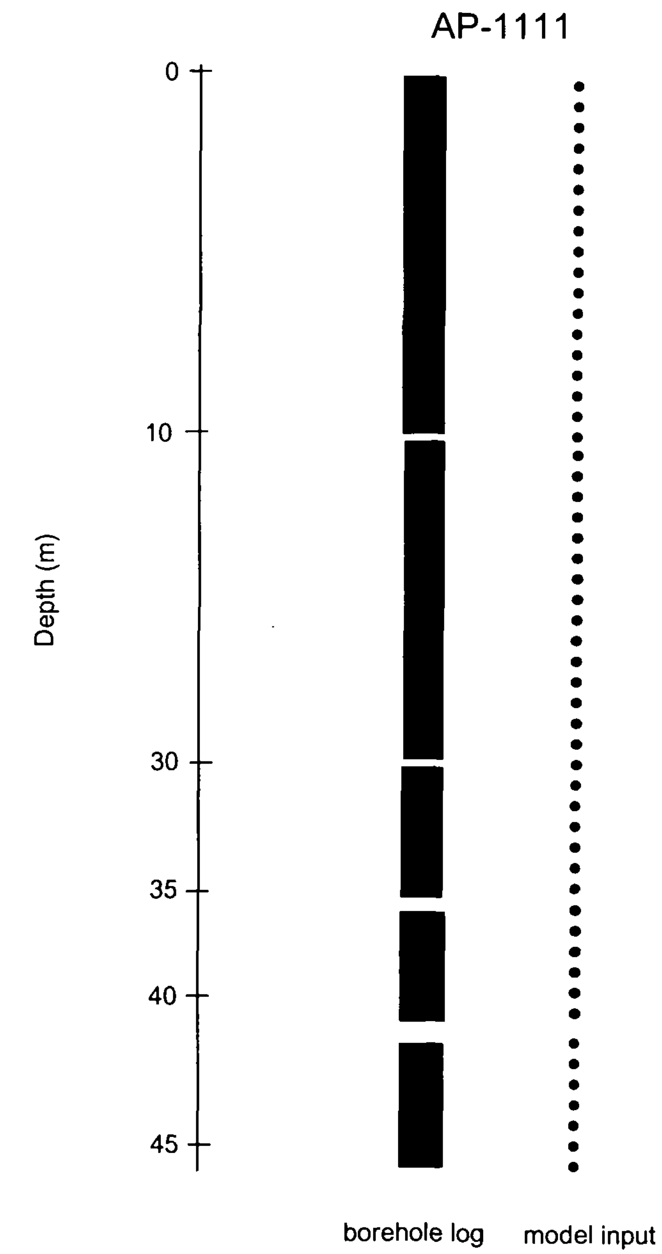
2004 Resistivity Model



2004 Resistivity (Cross-Section) Input



Borehole Input

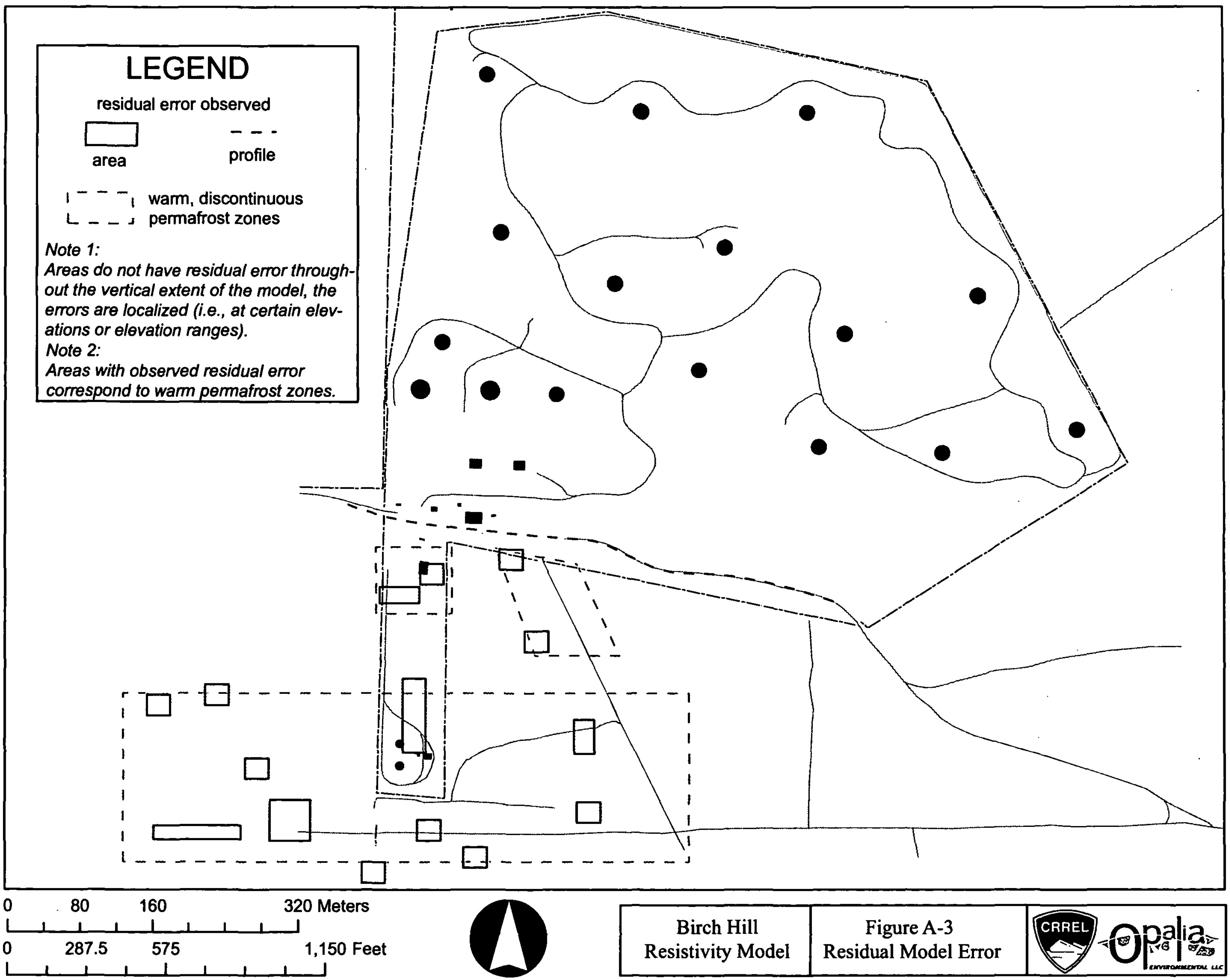


LEGEND

••••••••• frozen

••••••••• thaw

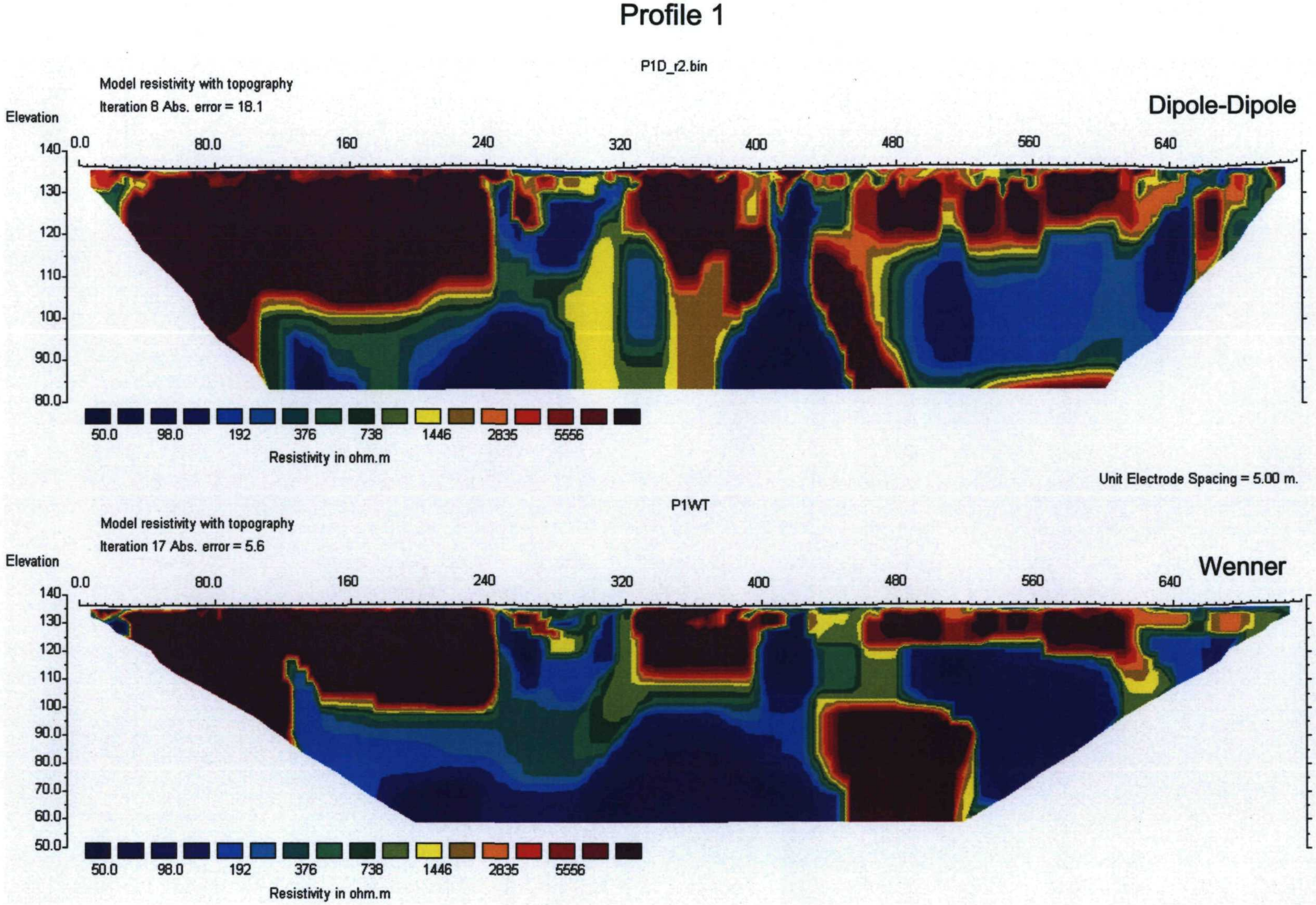
Birch Hill Resistivity Report	Figure A-2 Permafrost Model – Input Structure


LEGEND
residual error observed
area
profile
warm, discontinuous permafrost zones
Note 1:
Areas do not have residual error throughout the vertical extent of the model, the errors are localized (i.e., at certain elevations or elevation ranges).
Note 2:
Areas with observed residual error correspond to warm permafrost zones.
0 80 160 320 Meters
0 287.5 575 1,150 Feet
Birch Hill Resistivity Model
Figure A-3 Residual Model Error
CRREL
Opalia ENVIRONMENTAL LLC

APPENDIX B

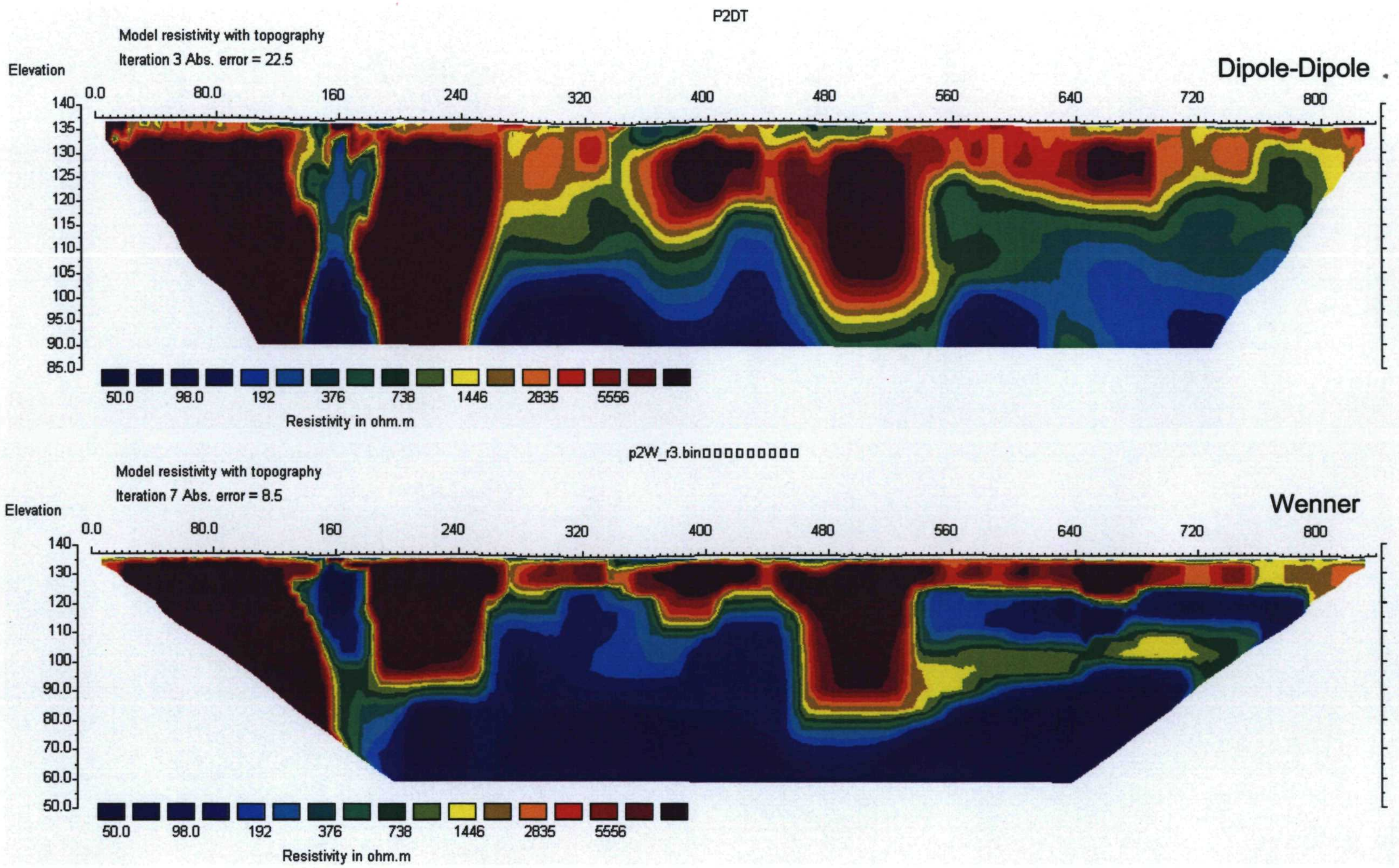
Appendix B Table 1: 2004 Resistivity Profile Data Collection Information

Profile #	Filename	Direction	Array Type	#Quads	Time (seconds)	Output Voltage	Depth levels 1	Other depth levels	1st electrode distance (m)	Last electrode distance (m)
1	P1W	W to E	W	768	1	50	16		5	480
1	P1W_r1	W to E	W	348	1	50	16		125	600
1	P1W_r2	W to E	W	348	1	50	16		240	715
1	P1D	W to E	D	861	1	50	4	6(2xa), 2(9xa)	5	480
1	P1D_r1	W to E	D	300	1	50	4	6(2xa), 2(9xa)	125	600
1	P1D2	W to E	D	718	1	200	2	5(4xa), 3(8xa)	125	600
1	P1D_r2	W to E	D	300	1	50	4	6(2xa), 2(9xa)	240	715
2	W5-31	E to W	W	768	1	50	16		0	475
2	W5_r1	E to W	W	348	1	50	16		120	595
2	P2W_r2	E to W	W	348	1	50	16		235	710
2	P2W_r3	E to W	W	348	1	50	16		355	830
2	D-5	E to W	D	583	1	100	3		0	475
2	D5_r1	E to W	D	200	1	100	3		120	595
2	D5_r2	E to W	D	200	1	100	3		235	710
2	D5_r3	E to W	D	200	1	100	3		355	830
3	P3W	N to S	W	768	1		16		0	475
3	P3D	N to S	D	752	1	200	10		0	475
3	P3D2	N to S	D	494	2	200	4		0	475
3	P3S	N to S	S	640	2	200	10		0	475
4	P4W	N to S	W	768	1	100	16		0	475
4	P4D	N to S	D	688	1	200	8		0	475
4	P4S	N to S	S	640	2	200	5	2(3xa), 3(5xa)	0	475
5	P5W	N to S	W	768	1	100	16		0	475
5	P5D	N to S	D	657	1	200	5	5(2xa)	0	475
5	P5S	N to S	S	671	2	200	5	4(3xa), 2(5xa)	0	475
6	P6W	W to E	W	765	1	200	15		15	490
6	P6W_r1	W to E	W	345	1	200	15		135	610
6	P6W_r2	W to E	W	345	1	200	15		255	730
6	P6W_r3	W to E	W	345	1	200	15		375	850
6	P6D	W to E	D	756	1	200	9		15	490
6	P6D_r3	W to E	D	657	1	200	9		375	850
6	P6S	W to E	S	715	1	200	11		15	490
6	P6S_r2	W to E	S	535	1	200	11		255	730
6	P6S_r3	W to E	S	275	1	200	11		375	850

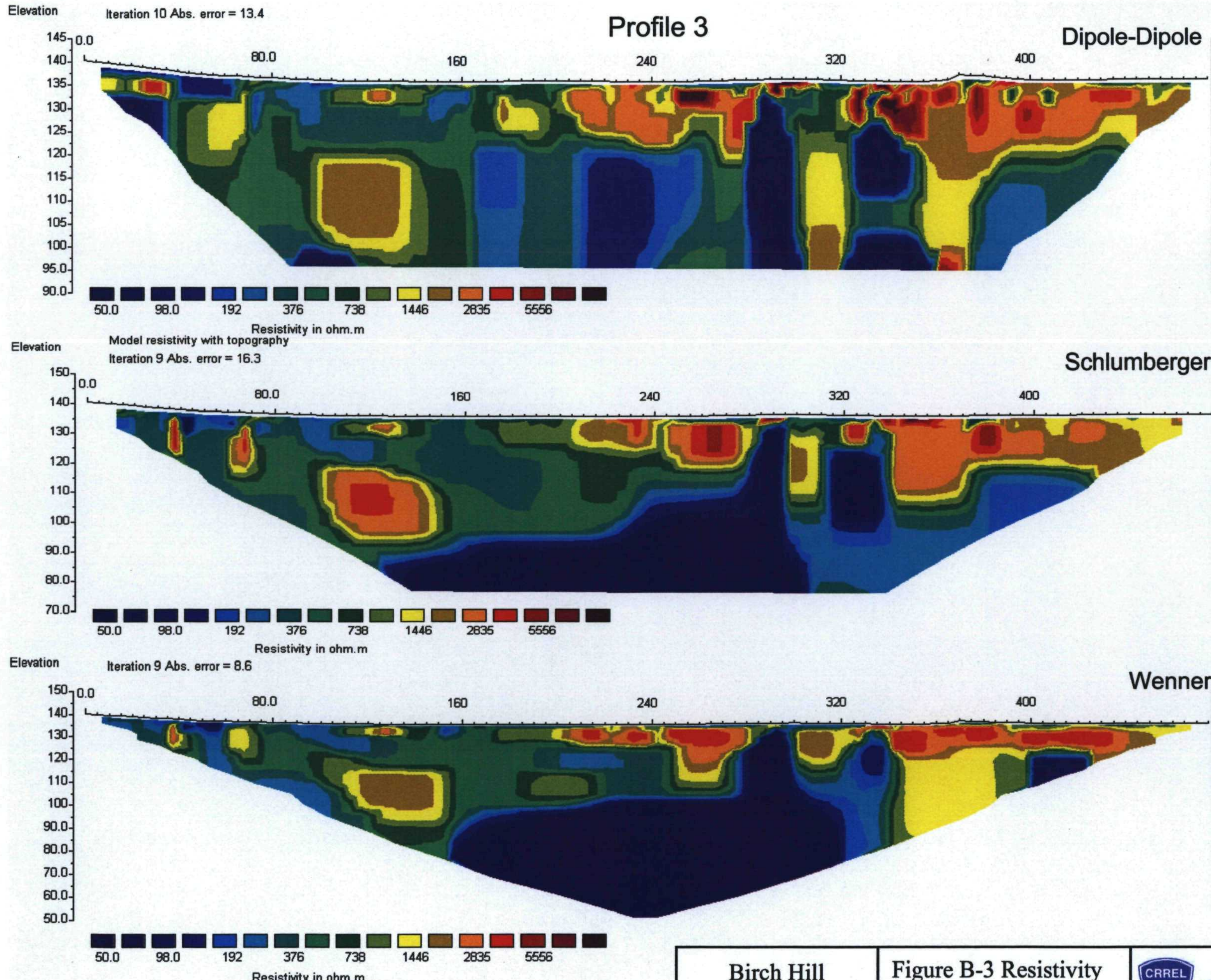


Birch Hill Resistivity Report	Figure B-1 Resistivity Inversions for Profile -1

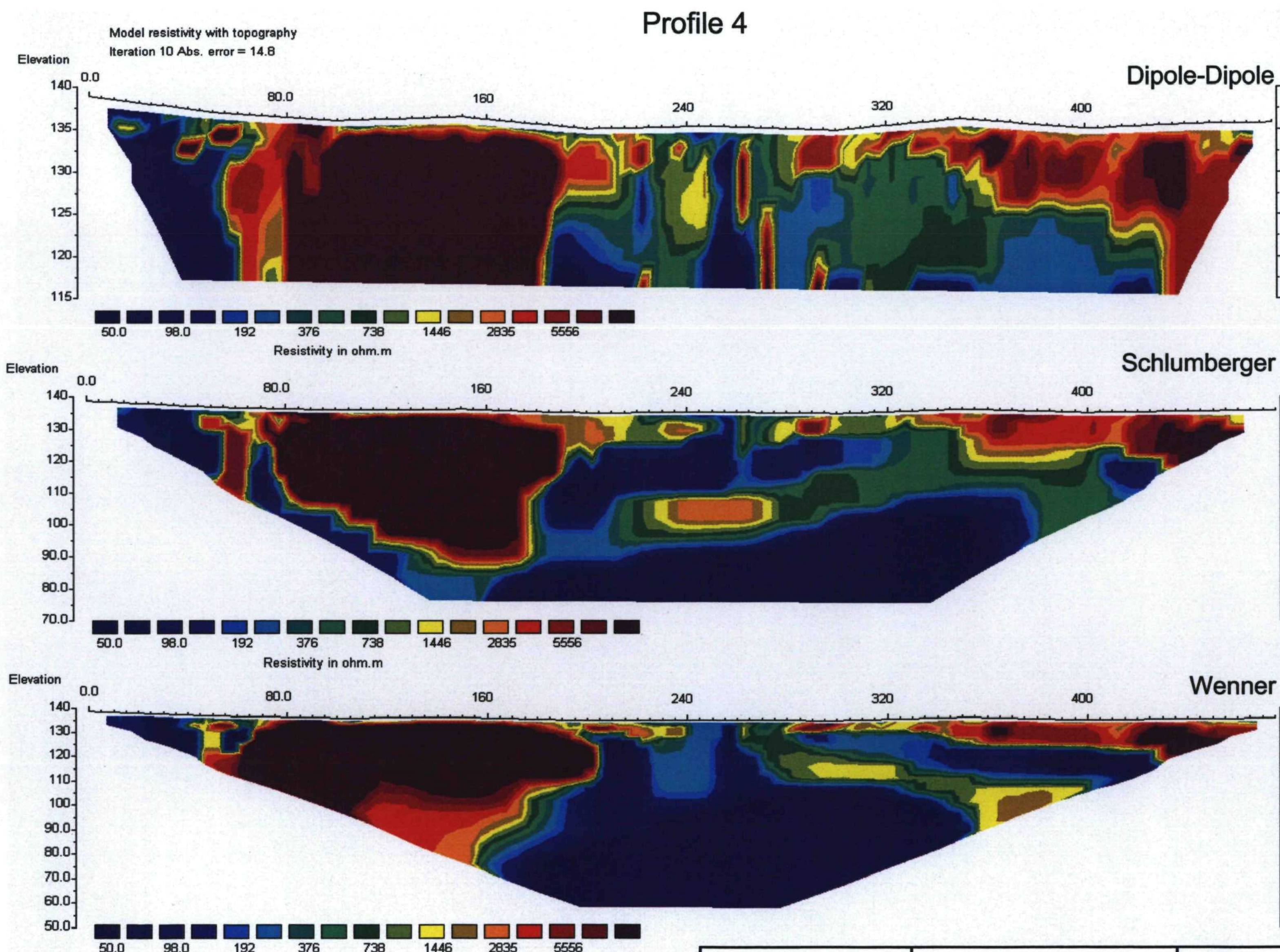
Profile 2



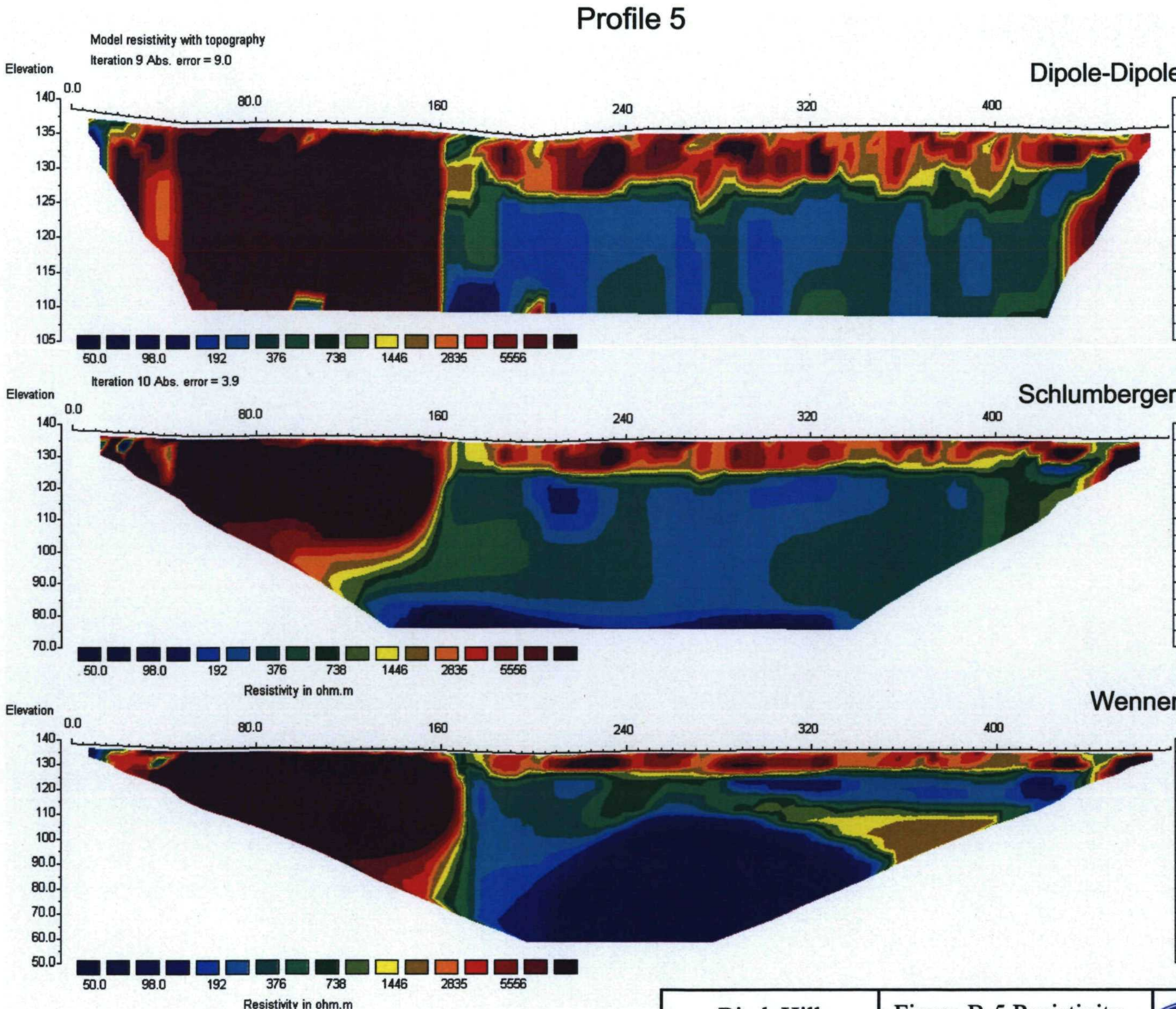
Birch Hill Resistivity Report	Figure B-2 Resistivity Inversions for Profile -2



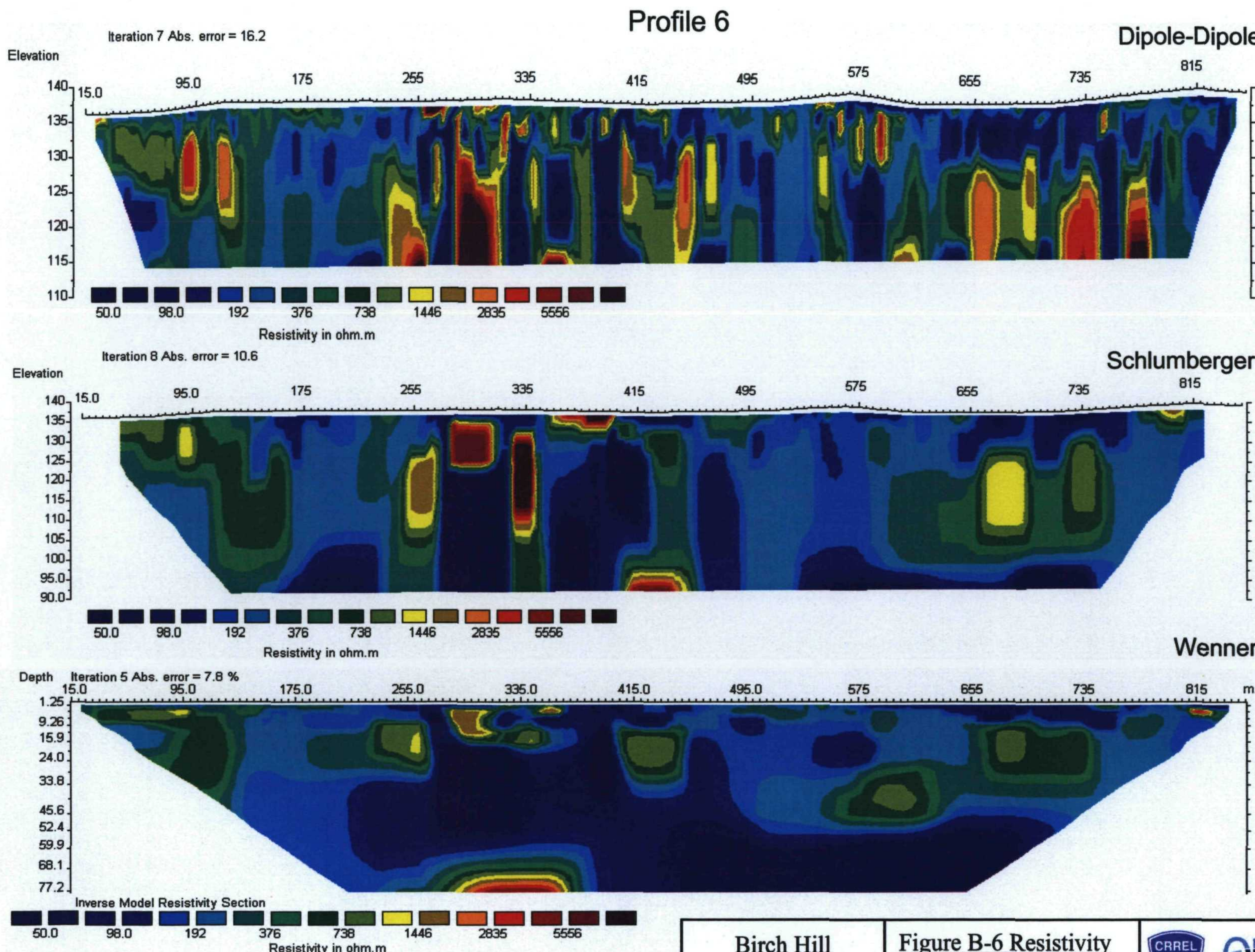
Birch Hill Resistivity Report	Figure B-3 Resistivity Inversions for Profile -3	CRREL Opalia ENVIRONMENTAL LLC



Birch Hill Resistivity Report	Figure B-4 Resistivity Inversions for Profile -4



Birch Hill Resistivity Report	Figure B-5 Resistivity Inversions for Profile -5



Birch Hill Resistivity Report	Figure B-6 Resistivity Inversions for Profile -6